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Membrane aerated biofilms for high rate biotreatment: performance appraisal, engineering principles, scale-up and development requirements

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ABSTRACT: Diffusion of the electron acceptor is the rate controlling step in virtually all biofilm reactors employed for aerobic wastewater treatment. The membrane-aerated biofilm reactor (MABR) is a technology that can deliver oxygen at high rates and transfer efficiencies, thereby enhancing the biofilm activity. This paper provides a comparative performance rate analysis of the MABR in terms of its application for carbonaceous pollutant removal, nitrification/denitrification and xenobiotic biotreatment. We also describe the mechanisms influencing process performance in the MABR and the inter-relationships between these factors. The challenges involved in scaling-up the process are discussed with recommendations for prioritization of research needs.

KEYWORDS: Membrane, biofilm, aeration, wastewater, reactor

Introduction

Background

Biofilms, which comprise a community of microorganisms attached to a surface, have long been exploited for wastewater treatment. Natural immobilization of the microbial community on inert supports allows excellent biomass retention and accumulation without the need for solid-separation devices. The ability of biofilm based processes to completely uncouple solids retention time (SRT) from hydraulic retention time (HRT) is especially useful for slow-growing organisms which would otherwise be washed out of the system, nitrifying biofilms being a case in point. Established biofilm processes, such as the trickling filter became popular in the 20th century because they offered simple, reliable and stable operation¹. Innovation in wastewater treatment technology is driven largely by the need to meet increasingly stringent regulatory standards and by the need to reduce the capital and operating costs of treatment processes. In recent years, these drivers have prompted the emergence of improved biofilm processes such as the Biological Aerated Filter (BAF)² and the Moving Bed Biofilm Reactor (MBBR)³. One of the key advantages of biofilm-based processes is the potentially high volumetric reaction rate that can be attained due the high specific biomass concentration. Unfortunately, this advantage is rarely exploited in full-scale processes as a result of oxygen transfer limitations into thick biofilms⁴. Biofilms in wastewater treatment systems are frequently thicker than the penetration depth of oxygen, typically 50µm to 150µm⁴ and, under high carbon-loading rates, the process becomes oxygen transfer rate limited. This problem, combined with the difficulty in controlling biofilm thickness has resulted in the application of biofilm technology predominantly for low-rate processes. Innovative technologies to overcome this problem are mainly based on methods that increase the specific surface area (particle based biofilm technologies),⁵ or on methods for increasing the oxidation capacity and efficiency, such as the membrane-aerated biofilm reactor (MABR), the subject of this review.

A previous review of the MABR was published in 1999⁶. Since then, interest in the technology has greatly increased, as demonstrated by the number of recent publications on the topic. In light of this, an updated review is timely, in order to appraise the current state of the technology, critically assess the

potential of the MABR and provide recommendations on future developmental requirements. The scope of the review is restricted to membrane attached biofilms in which oxygen is transferred across the membrane for the oxidation of wastewater. Analogous configurations involving membrane attached biofilms, such as the hydrogenotrophic reactor⁷, the membrane biofilter⁸ and the extractive membrane bioreactor⁹ are not examined here.

Historical Perspective

The incorporation of membranes in wastewater treatment reactors can be traced back several decades when Schaffer et al¹⁰ reported the use of plastic films of unspecified material for oxygenation of a wastewater. Visible biological growth was observed on the polymer and it was reported that this had no observable effect on the oxygen transfer rate. It was not until 1978 when Yeh and Jenkins¹¹ reported results of experiments with Teflon tubes in synthetic wastewater, that the potential of the membrane for oxygenation was recognized. This work was inspired by the emergence of hollow fiber oxygenation systems for cell and tissue culture in the early 1970s¹². By 1980 the first patent was filed for a hollow fiber wastewater treatment reactor in which the biological oxidation takes place on the surface of microporous membranes¹³. However, commercial exploitation of the technology has not yet emerged and until the present time there have been very limited trials of the technology beyond laboratory scale.

Membrane-aerated biofilms: operational principles, advantages and current limitations

In the MABR, the biofilm is naturally immobilized on an oxygen permeable membrane. Oxygen diffuses through the membrane into the biofilm where oxidation of pollutants, supplied at the biofilm-liquid interface takes place. The oxygen supply rate can be controlled by the intra-membrane oxygen partial pressure and membrane surface area. Since oxygen and soluble wastewater constituents are supplied from opposite sides of the biofilm, a unique nutrient profile and, consequently, microorganism population profile develop in the MABR. Figure 1 shows schematically the diffusive and advective fluxes of oxygen and typical soluble wastewater constituents in a membrane-aerated biofilm. The

aerobically active region occurs where both oxygen and nutrients are simultaneously available within the biofilm. Above a critical biofilm thickness, depending on the loading rate, reaction kinetics and mass transfer resistances, an oxygen depleted zone can exist. In the context of nitrogen removal, the existence of an anoxic zone at the biofilm-liquid interface is advantageous for denitrification. The factors determining the location and thickness of the aerobically active region are primarily dependent upon the ratio and magnitudes of the carbon substrate loading to the intra-membrane oxygen pressure¹⁴. The existence of spatial stratification of microbial activity, but more importantly the ability to manipulate its location and thickness has permitted the MABR to be applied to simultaneous nitrification/denitrification¹⁵ and trichloroethane (TCE) biodegradation by cometabolism¹⁶.

It is apparent that the MABR has several advantages over conventional biofilm technologies;

- Comparatively high volumetric carbon oxygen demand (COD) removal rates are achievable if pure oxygen is fully exploited and if biofilm thickness control measures are in place.
- Bubbleless aeration offers the potential for significantly higher oxygen utilization efficiencies with consequent energy savings. In addition, reduced air stripping during the biotreatment of volatile organic compounds is possible.
- Simultaneous nitrification, denitrification and COD removal can be achieved at comparatively higher rates due to the unique microbial population stratification.
- Specialist degrading microorganisms, such as ammonia oxidizing bacteria, tend to be preferentially located adjacent to the biofilm-membrane interface thereby enhancing their retention by protection from biofilm erosion¹⁷.

At present there are several unresolved problems with the process that have hampered the implementation of the technology at technical scale, these include

- Difficulty in maintaining an optimum biofilm thickness that is sufficient to provide enough oxidation capacity but not so excessive to cause liquid flow distribution problems

- The possibility that membrane defects will cause significant process upset.
- The potentially high costs of liquid pumping in a fully loaded membrane module and the cost of maintaining a supply of pressurized pure oxygen
- Unknown membrane strength and long-term durability in the wastewater milieu.
- Poor understanding of scale-up rules for membrane modules.

Despite these drawbacks, over a hundred research articles concerning both fundamental and applied aspects of the MABR have been published for a range of wastewater treatment application areas. The increased interest in the MABR has arisen perhaps due to a realization that it is a technology that can fully exploit the potential of biofilms in biotreatment processes.

Critical assessment of MABR process performance

Organic carbon removal

Due to the low solubility of oxygen in water, the maximum oxygen diffusion rate in conventionally aerated biofilms is typically *ca.* $10 \text{ g m}^{-2}\text{d}^{-1}$ which is low enough to cause oxygen limitation in many biofilm based aerobic wastewater processes¹⁸. However, with the use of pure oxygen, MABRs have the potential to offer significantly higher oxygen transfer rates. Quantitative performance comparisons between the MABR and conventional biofilm technology must be considered in view of the predominant use of pure oxygen in the former, however, with dead-end operation or with appropriate control of gas flow in open end configurations, higher oxygen conversion efficiencies are achieved in the MABR (up to 100%) compared to conventional bubble aeration^{17, 19}. Maximum Standard Oxygen Transfer Efficiencies for conventional aeration at 4.5m depth are typically 25 to 35%²⁰.

A representative sample of MABR performance data is summarized in Table1. It can be seen that the volumetric COD removal rates in the MABR are, in many cases, higher than those achieved in BAFs, MBBRs, rotating biological contactors and high-rate trickling filters, where removal rates are typically in the region of $5\text{-}8 \text{ kg}_{\text{COD}} \text{ m}^{-3} \text{ day}^{-1}$, $1\text{-}4 \text{ kg}_{\text{COD}} \text{ m}^{-3} \text{ day}^{-1}$, $2.5\text{-}6 \text{ kg}_{\text{BOD}} \text{ m}^{-3} \text{ day}^{-1}$ and $0.5\text{-}1 \text{ kg}_{\text{BOD}} \text{ m}^{-3} \text{ day}^{-1}$.

¹, respectively²⁰. The potential for high specific oxidation rates was the impetus for early investigations of the technology, where the emphasis was on the oxidation of soluble carbonaceous pollutants. Yeh and Jenkins¹¹ first reported that MABRs, using pure oxygen and sealed ended membranes outperformed both conventional biofilm reactors and activated sludge systems under conditions of high organic loading. 91% BOD removal was achieved at a loading rate of $4.9 \text{ g}_{\text{BOD}} \text{ m}^{-2} \text{ d}^{-1}$ and a detention time of 2h. Pankhania *et al.*²¹, using a similar configuration but with polypropylene sealed-end membranes, demonstrated organic carbon removal fluxes of up to $42.7 \text{ g}_{\text{COD}} \text{ m}^{-2} \text{ d}^{-1}$. In one of the most comprehensive studies on the MABR applied to COD removal²², a pilot scale MABR was employed to treat high strength wastewater sourced from cider manufacturing. Two hollow fiber reactors were operated for 90 days one in plug flow and the other in mixed flow regime, in each case a range of loading rates were applied. Steady-state removal fluxes at the highest loading rates were $62.6 \text{ g}_{\text{TCOD}} \text{ m}^{-2} \text{ d}^{-1}$ (81% at HRT 1.4 h), and $60.4 \text{ g}_{\text{TCOD}} \text{ m}^{-2} \text{ d}^{-1}$ (88% at HRT 1.8 h) for completely-mixed and plug flow operation respectively. However, there was a significant difference in the removal rates of dissolved COD and suspended COD, with the dissolved COD having removal efficiencies over 90% while the suspended solids removal varied from 40% to 80%. The process was also tested for its ability to cope with shock loading. A threefold increase in the influent COD over two HRTs reduced the COD removal efficiency to 64% but the performance recovered completely after three HRTs. A twofold increase in the volumetric flowrate at constant COD concentration had a more prolonged effect and full recovery in performance was not achieved after four HRTs.

Nitrogen removal

Nitrification is a microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate. Nitrification is primarily accomplished by aerobic autotrophic bacteria that can build organic molecules using energy obtained from inorganic sources, in this case ammonia or nitrite. Various groups of heterotrophic bacteria and fungi can also carry out nitrification, although at a slower rate than autotrophic organisms. Denitrifying organisms are predominantly facultative heterotrophs that reduce nitrate in the absence of molecular oxygen. The

organic content of the wastewater is the energy source for denitrification. In many wastewater treatment plants, denitrification is generally conducted in a separate anoxic reactor with various recycle systems. The complexity of these processes has led to the search for new processes where simultaneous nitrification and denitrification can be achieved in a single stage.

There are three principal reasons for the interest in applying MABR technology for nitrogen removal;

- As a result of the unique microbial stratification profile in MABRs, as shown schematically in Figure 1, the potential exists for simultaneous nitrification, denitrification and COD removal in a single biofilm. Nitrifiers, are preferentially located in the oxygen rich region adjacent to the membrane biofilm interface while denitrifiers grow in the anoxic region at the biofilm liquid interface where the COD concentration is typically at its highest value.
- The half-saturation constant with respect to oxygen for Ammonia Oxidizing Bacteria (AOB) is significantly higher than for aerobic heterotrophs, the consequence of which is that in conventional biofilms the nitrifying bacteria are generally out-competed by the heterotrophs unless the carbon concentration is low ²³. MABRs may offer a performance advantage, particularly in their ability to maintain a relatively high ratio of nitrifiers to heterotrophs.
- Nitrifiers tend to be sensitive to shock loads and thus, the unique spatial stratification may offer a protected niche. The nitrifiers, which generally have lower growth rates than the heterotrophs and are more susceptible to inhibition and may be partially protected from bulk liquid inhibitors by a heterotrophic layer adjacent to the biofilm liquid interface.

Table 2 summarizes data from selected studies where sufficient information was provided with respect to reactor configuration, operating conditions and performance in order to make meaningful comparisons. For a variety of reasons, a significant number of laboratory scale investigations of MABR performance have used configurations where the specific surface area is comparatively low. For this reason, performance comparisons are better assessed by flux based loading and removal rates.

In early MABR application studies low rates of nitrification but very high organic carbon oxidation were reported by both Yeh and Jenkins ¹¹ and Pankhania *et al.* ¹⁹. In both cases the low rates of

nitrification were attributed to the wash out of slow growing chemoautotrophic nitrifying bacteria. Timberlake¹⁵ first applied the MABR to demonstrate simultaneous carbon substrate oxidation, nitrification and denitrification in a single biofilm. It was hypothesized that the high oxygen concentrations at the membrane biofilm interface would support nitrification, an aerobic heterotrophic layer above this would facilitate COD pollutant removal and an anoxic layer close to the biofilm-liquid interface would allow denitrification. Although simultaneous carbon substrate oxidation, nitrification and denitrification was achieved in this study, the removal efficiencies achieved were low by comparison with typical wastewater treatment systems, for example COD removal efficiencies were approximately 50%, nevertheless, the potential of the concept was proven. Studies by Suzuki *et al.*²⁴ showed that the thickness of a denitrifying layer affected the oxygen transfer rate and that it was necessary to control the biofilm thickness by sloughing in order to maintain high oxygen transfer rates for effective nitrification. Early confirmation of the microbial community stratification in MABRs was shown by Yamigawa²⁵ who compared, using most probable number (MPN) counts, the population of nitrifiers and denitrifiers at the interior of the biofilm, adjacent to the membrane, to those at the biofilm-liquid interface. It was shown that the nitrifying organisms predominated at the oxygen-rich region of the biofilm, while the denitrifying organisms were preferentially located adjacent to the oxygen-depleted biofilm-liquid interface. Simultaneous organic removal and nitrification occurred due to the stratified biofilm structure and nitrification rates comparable with those of conventional nitrification reactors were observed. Hibiya²⁶ used a fluorescent *in situ* hybridization (FISH) method to measure the spatial composition of the community structure in a membrane-aerated biofilm. Again, it was verified that the AOB were generally concentrated adjacent to the membrane-biofilm interface while the denitrifying bacterial were generally located in the anoxic regions, predominantly in the suspended sludge rather than at the biofilm-liquid interface. Terada *et al.*¹⁷ observed simultaneous nitrification and denitrification with overall average nitrogen removal of 83%. Using FISH it was shown that AOB predominated at the biofilm-membrane interface and were not detected at the biofilm-liquid interface. While this promoted good nitrification and the retention of the AOB in the biofilm, the possibility of

diffusional limitation in thick biofilms and the consequent necessity of biofilm thickness control was noted. The steady-state biofilm thickness was 1600 μm and DO measurements revealed that the oxic zone was 300 μm and 700 μm with and without substrate feeding respectively. Because the anoxic zone was quite a substantial proportion of the biofilm and also because of the lack of excess sludge, it was suggested that that denitrification occurred in the biofilm rather than in the sludge. Denitrification did not occur in the early stages of biofilm development since oxygen penetrated the entire biofilm. Semmens et al ²⁷, showed that the MABR could achieve 95% COD removal at $10 \text{ g m}^{-2}\text{day}^{-1}$ and essentially complete denitrification in a reactor that consisted of two connected vertical tubes containing bundles of hollow fiber microporous membranes. Recycled air was sparged into the modules both to promote liquid mixing to promote biomass control. The reactor operated for 190 days but towards the end of the operational period severe clogging occurred and subsequent inspection of the module showed that thick biofilm had joined many of the fibers together, thereby significantly reducing the wastewater contact area. It was apparent the gas bubbling was non-uniform and ultimately inadequate for biomass control. Satoh ²⁸ studied the effect of different COD loading rates and oxygen partial pressures on performance in an MABR, the use of microelectrodes for O_2 , NH_4 , NO_2^- , NO_3^- and pH allowed the specific rates and regions of nitrification and denitrification to be determined in the biofilm. Simultaneous nitrification denitrification and COD removal was achieved. The carbon and oxygen loading rates had no effect on the location of the nitrification and denitrification zones. However, denitrification performance was shown to be dependent on the thickness of the anoxic layer. Cole et al ²⁹ conducted a comprehensive analysis of the stratification of microbial respiratory activity and community structure in separate experiments under different fluid flow velocities and using different intra-membrane oxygen partial pressures. Steady-state biofilms were thick so that oxygen penetration was partial leaving an anoxic zone that ranged in size from 30% to 75% of the entire biofilm thickness. Simultaneous nitrification and denitrification occurred, however, the concentration and location of both AOB and denitrifiers was highly dependent on fluid velocity over the biofilm with very little AOB detected at low fluid velocities.

The aforementioned studies provide ample evidence confirming the relationship between the unique stratification in MABRs and the ability to achieve simultaneous nitrification and denitrification. Long term performance appears promising with continuous operation reported up to 350 days¹⁷. However, rates of denitrification are highly variable and would seem to depend on the attainment of an optimum biofilm thickness and the retention of denitrifying organisms following washing procedures.

Autotrophic aerobic nitrification

A small number of studies have been conducted to examine the performance of the MABR for the treatment of nitrogenous wastewater with very low C/N ratios³⁰⁻³³. Brindle *et al.*³¹ demonstrated very high steady-state specific nitrogen removal rates of up to 6.6 gNH₄-N m⁻² d⁻¹ with close to 100% oxygen conversion efficiency in a sealed end, pure oxygen hollow fiber MABR operating for up to 172 days. The membrane specific surface area and packing density were 185 m²m⁻³ and 1.3% respectively, these are comparatively low and there were no problems with excess biomass, suggesting that greater volumetric nitrification rates could be achieved by increasing the membrane area. Further trails by Hsieh *et al.*³² and Terada *et al.*³⁴ confirmed the feasibility of the process for long term operation.

Investigations of the microbial community structure in autotrophic MABRS were first reported by Schramm *et al.*³⁵. The spatial distribution of nitrifying bacteria of the genera *Nitrosomonas*, *Nitrospira*, *Nitrobacter* and *Nitrospira* were conducted using fluorescence in situ hybridization (FISH) in combination with confocal laser scanning microscopy. Gradients of oxygen, pH, nitrite and nitrate were determined by means of microsensors. The oxic part of the biofilm, adjacent to the biofilm membrane interface was dominated by ammonia oxidisers such as *Nitrosomonas europaea* and by members of the genus *Nitrobacter*. In the totally anoxic part of the biofilm, adjacent to the biofilm liquid interface, cell numbers of all nitrifiers were relatively low. Terada *et al.*³⁶ used mathematical modeling to investigate the relative performance of an MABR over conventional biofilms consisting of aerobic ammonia oxidizing bacteria (AeAOB), aerobic nitrite oxidizing bacteria (AeNOB) and anaerobic ammonia oxidizing bacteria (AnAOB) in terms of total nitrogen(T-N) removal efficiency.

The MABR was found to be advantageous particularly with respect to its ability to maintain high T-N removal under conditions where fluctuations in loading rate are to be expected. In a follow-up modeling study, Lackner et al³⁷ examined the effect of COD originating from autotrophic decay products on performance and community structure in an MABR compared to conventional biofilms. It was found that heterotrophic supported by microbial decay products could have a significant effect on the T-N performance in the MABR under high ammonium loads. Simulations were conducted to monitor the microbial community structure following the introduction of COD to the influent. Anaerobic ammonium oxidation could not be sustained in the MABR while 50% of the T-N removal in the conventional biofilm was accounted for by anaerobic ammonium oxidation.

These recent studies highlight the complexity of the microbial community structure in biofilms applied to the treatment of nitrogenous wastewater. It is clear that the spatial stratification of microbial communities in the MABR is distinct and may be manipulated by nitrogen and oxygen loading rates, but a significant amount of work is still required to understand the mechanisms that will allow the exploitation of the MABR for high-rate removal of nitrogen from wastewater.

Hybrid MABRs for nitrogen removal

Recently, there have been a number of efforts to develop hybrid MABRs for the application of total nitrogen removal³⁸⁻⁴². Kapell et al⁴⁰ incorporated membrane aerators into anaerobic bioreactors treating high strength wastewater. Because oxygen only penetrates a short distance from the membrane surface, nitrification and aerobic heterotrophic oxidation took place in the biofilm, while the bulk liquid phase remained anaerobic providing a suitable environment for fermentative and methanogenic activity. The initial results appear to be promising, however, improved COD removal efficiencies (from 65% to 95%) were balanced by significantly reduced biogas production. Good nitrogenous removal efficiencies (greater than 95%) were only achieved when the influent COD concentration was reduced by approximately 50%. Terada et al⁴¹ described results from a hybrid reactor whereby the nitrification occurred in the membrane-aerated biofilm while the bulk liquid was cycled between oxic/anoxic

conditions as a method to enhance biological phosphorous removal. A similar concept was investigated by Downing and Nerenberg⁴² whereby the membrane aerated biofilm was intended for nitrification whilst denitrification would occur in the bulk liquid. Under COD free conditions the nitrification rate reached $1.65 \text{ g}_N \text{ m}^{-2}\text{day}^{-1}$. After adding acetate, the bulk dissolved oxygen concentration dropped, nitrification decreased to $0.85 \text{ g}_N \text{ m}^{-2}\text{day}^{-1}$ but denitrification occurred resulting in a total nitrogen removal of 75% and greater than 93% COD removal. These three recent studies suggest that it may not be necessary to rely on an anoxic outer region in the biofilm for denitrification, thereby partly mitigating the need to maintain the biofilm thickness between a narrow range to maintain optimum bioreactor productivity.

Application of the MABR for degradation of xenobiotic pollutant streams

Biofilm based reactors are the preferred option for treatment of xenobiotic degrading wastewater streams on account of their ability to retain slow growing specialist microorganisms independent of detention time and the presence of microenvironments that promote diverse microbial communities that can degrade a wide range of contaminants and withstand shock loads. The biological fluidized bed reactor is commonly employed for the aerobic treatment of xenobiotic wastewater; however it requires a constant high liquid velocity to maintain the fluidized bed and the stripping of volatile components from the liquid.²⁰ The MABR has emerged as a promising alternative technology for several reasons;

- Bubbleless operation minimizes air-stripping of compounds with high Henry's Law constants such as BTEX⁴³;
- The creation of and ease of manipulation of a defined oxic/anoxic micro-environment can be advantageous for the degradation of compounds with problematic intermediates⁴⁴
- Gaseous substrate mixtures (e.g. methane/oxygen), which are necessary for some cometabolism processes can be transferred to the biofilm from opposite sides, thereby preventing the formation of explosive gas mixtures^{16 45}

A number of laboratory scale studies have investigated the potential of the MABR for the biotreatment of synthetic wastewater with xenobiotic constituents as can be seen in Table 3. Comparative performance analysis is difficult, given the diverse range of technologies, operating parameters and wastewater constituents and, accordingly, the performance data in Table 3 are expressed in the units specific to the pollutant in question. It appears that, under optimized conditions, the MABR seems to provide high removal efficiencies at loading rates that can be expected to be reasonable. Some noteworthy performance studies are briefly summarized as follows; Debus and Wanner⁴³ first showed, using a validated mathematical model, that for MABRs applied to the treatment of volatile pollutant, an optimum biofilm thickness exists. Suboptimal thicknesses lead to back-diffusion of the volatile components into the membrane lumen, while excessive biofilm thicknesses lead to mass transfer limitations and consequently reduced reaction rates. Kolb and Wilderer⁴⁶ employed a novel configuration combining a CSTR with either an internal or external membrane aeration module. Here the fluid flow conditions surrounding the biofilm can be controlled independently of the process flow rate to maximize mass transfer and optimize biofilm growth. Activated carbon was added to dampen concentration variations. Ohandja and Stuckey,⁴⁴ studied the degradation of perchloroethylene in a flat sheet MABR configuration and reported a removal rate of $547 \text{ mmol m}^{-3} \text{ hr}^{-1}$ which is believed to be the highest value ever reported for this compound.

A small number of studies have investigated the MABR under sequencing batch operation. This mode of operation is considered advantageous in responding to shock loads. Woolard and Irvine⁴⁷ found that operating in sequencing batch mode was superior in coping with shock loads than a continuous flow MABR when applied to the degradation of phenol. Wobus et al⁴⁸ found that the higher concentration due to the shock load could be dealt with in the SBBR by dilution and lengthening of the batch time to degrade all the pollutant. Wobus et al⁴⁸ and Wobus and Roske⁴⁹ compared identical reactors using chlorophenol mixtures as a model pollutant stream. Under steady loading conditions both operating modes demonstrated similar performance levels although there were differences in the biomass distribution (uniform in the sequencing batch reactor, axial gradients in the continuous flow reactor).

However, under shock loading conditions superior performance was achieved in the sequencing batch mode of operation.

Unfortunately no reports have yet emerged where the MABR is benchmarked against conventional biofilm processes using identical wastewater streams and comparable operating conditions. From the limited studies reported to-date, it appears that MABR has the potential for the effective removal of xenobiotic compounds and there is some preliminary evidence demonstrating superior performance over conventional technologies. However, several aspects of MABR design and operation need to be explored in further detail before the process can become a viable alternative for xenobiotic biodegradation;

- Performance characterization with wastewater containing complex mixtures of constituents representative of industrial wastewater or leachate.
- Assessment of the effect of soluble organic wastewater constituents on membrane durability and long term mass transfer performance.
- Quantitative analysis of the degree of VOC stripping to the membrane lumen, particularly under transient operating conditions, start-up or after biofilm loss due to sloughing.

Engineering aspects of MABR design, scale-up and operation

Introduction

Process performance is ultimately determined by the rate and efficiency at which desired pollutants are removed from the influent wastewater. In the MABR, the interrelationship between the biofilm properties (density, thickness, microbial ecology and the associated kinetics of each microbial species in the community) and the resistances to mass transfer (membrane permeability, concentration boundary layer at the biofilm-liquid interface, diffusive resistance of the biofilm matrix) determine the net reaction rate. Figure 2 schematically describes the interrelationships between the various parameters

that influence overall performance. Some of the most important considerations for MABR design, scale-up and operation are described in this section.

Membrane material selection

A wide range of membrane materials have been employed in MABR studies to-date, and can be categorized as microporous, dense (non-porous) or composite. Microporous membranes are manufactured from hydrophobic materials such as polypropylene or polyethylene. Oxygen is transported across the membrane via gas-filled pores and, because of the comparatively large diffusion coefficient in the gas phase, high oxygen transfer rates can be achieved⁵⁰. However, there is some evidence to suggest the oxygen transfer performance can deteriorate over time due to the accumulation of water in the pores or the colonization of the pores by bacteria^{51 52}. Microporous hydrophobic membranes must be operated below their bubble pressure in order to prevent the detachment of biofilm by bubbles and this constraint may become a rate limiting factor if the a high oxygen transfer rate is required. It was noted by Cote et al⁵⁰ that for hydrophobic membranes the observed bubble point occurred at a much lower pressure than was predicted by calculations thereby further reducing the practicable intra-membrane operating pressure.

Non-porous or dense membranes have been employed in numerous MABR trials, typically using silicone rubber tubing with pure oxygen in the membrane lumen. Although the wall thickness, and hence diffusional resistance, of such membranes are significantly thicker than that for micro porous membranes, the intra-membrane oxygen pressures applied can be significantly higher. By using reinforced silicone membranes. Kolb and Wilderer⁴⁶ suggested that high pressures can be used, thus overcoming oxygen limitation even during the treatment of high strength wastewater in systems where thick biofilms had developed. Silicone has a high oxygen permeability and is the membrane of choice in when applied to the aeration of medium scale cell-culture bioreactors⁵³. A further advantage of such membranes is that they are comparatively resilient to chemical and physical abrasion⁵³.

Composite membranes, in which a thin coat of non-porous gas permeable material (e.g. polyurethane or polydimethylsiloxane) is embedded in or coated on a porous membrane appear to be a promising development in the effort to develop robust aerators that deliver high oxygen transfer rates without the difficulties associated with traditional porous membranes, such as low bubble points⁵⁴. A small number of studies have applied this type of membrane^{22, 42}, however, no detailed analysis has yet been reported on the benefits of such membranes on MABR performance. A novel membrane concept was proposed by Motlagh et al⁵⁵ in which a stitched hollow fiber membrane fabric acted as a biofilm support. It was proposed that wastewater would be transported through the membrane-biofilm structure and thus, it was suggested that, nutrient transfer rates to the biofilm would be enhanced by advective transport. To-date, this concept has been explored only by mathematical modeling⁵⁵.

Membrane module configuration

Several configurations of membrane module have been reported including hollow-fiber, flat sheet or spiral wound. Hollow fiber modules are similar to those used in microfiltration applications and have membrane diameters ranging from tens of micrometers to millimeters. High specific surface areas can be achieved, but, when tightly packed are susceptible to biofilm clogging²⁷. A useful approach has been to operate in dead end mode with free movement of the membrane tubes in the module, this reportedly offered greater flexibility in terms of excess biomass removal during cleaning operations²², however, bacterial growth distribution was not uniform along the length of the fibers³¹, this could be attributed to axial gradients in lumen gas composition. The use of flat sheet membranes in MABR studies^{15, 52, 56} is less common, perhaps due to the lower specific surfaces area available, but they have been useful, for example, in microscopic analysis⁵⁷ and microelectrode studies on laboratory-scale membrane aerated biofilms⁵⁸. Spiral wound membrane configurations have been used in a few studies^{49, 59} these are easily assembled and when wound into a tight helix but do not provide a very high specific surface area. There are no reports of experimental comparisons between various MABR membrane configurations, but a Computational Fluid Dynamics (CFD) model study⁶⁰ provided some evidence that liquid flow

distribution in multiple flat-sheet modules would be superior to that in hollow fiber modules in terms of mitigating flow maldistribution.

Factors influencing oxygen transfer rate

In terms of gas supply all membranes types can be operated in with either a dead-end or continuous flow operation in the lumen. Dead end operation can theoretically offer up to 100% oxygen utilization¹⁷,¹⁹, however, the oxygen transfer rate can be reduced by water condensation and/or the accumulation of carbon dioxide creating axial gradients in the lumen. In contrast, open-ended operation can flush out carbon dioxide and any water vapor. This operational mode eliminates axial gradients in the gas phase but inevitably will have oxygen utilization efficiencies of less than 100%. The intra-membrane oxygen pressure and the membrane mass transfer coefficient, k_M , determine rate of transfer oxygen to the biofilm. If anaerobic/anoxic degradation is required then the oxygen pressure must be carefully balanced to maintain the anoxic zone at the biofilm-liquid interface. For the treatment of high-strength wastewaters the intra-membrane oxygen pressure is likely to be the rate controlling factor. As a general guideline, thin-walled microporous membranes can be expected to have a high value of k_M , but a comparatively low maximum pressure, while dense (silicone) membranes will usually have a lower value of k_M but a higher maximum pressure. Microporous membrane are typically operated at in the region of 0.1 to 0.5 bar, while silicone membranes, can operate at up to 3 bar or 6 bar if reinforced⁶¹. Stress tests on commercially obtainable non-reinforced silicone membranes, with outer and inner diameters of d_2 and d_1 respectively, show that maximum pressure can be described by the following expression.

$$p_{max} = 2\sigma \left(1 - \frac{d_1}{d_2} \right) \text{ with } \sigma = 4 \cdot 10^5 \text{ N/m}^2.$$

Biofilm thickness control

Biofilm thickness control is perhaps the most significant scale-up challenges for the MABR. Excessive biofilm causes flow maldistribution in the membrane module with consequent channeling

and clogging²⁷. Ideally, it would be desirable to maintain a constant biofilm thickness by operating the MABR in a manner that achieves equilibrium between biomass accumulation and detachment/endogenous decay. Unfortunately biofilm detachment rate is highly variable and is very difficult parameter to control in practical operations. Detachment occurs predominantly as a result of either erosion or sloughing, the distinction is made based on the size of particles removed⁶²; sloughing is associated with the removal of large sections of the biofilm from the support. Detachment rate cannot be directly correlated to the imposed shear force⁶³ and, although an increase in fluid shear can result in a temporary increase in detachment rate⁶⁴, the full set of mechanisms describing biofilm detachment is poorly understood. At present, biomass control strategies for long-term MABR operation require the use of intense scouring methods that result in severe biofilm sloughing. For example; Pankhania et al²¹ sequentially applied air scouring (10s) followed immediately by water flushing (60s) repeated three times; Brindle et al²² simultaneously applied a wash water flow of 4-6 L/min and an air flow of 30-40 L/min for a period of 10 to 15 s, this procedure was undertaken on average every two days during long term MABR operation, the approximate volume of wash water required was 9% of the wastewater treated; Terada et al¹⁷ used liquid washing (60s) at 18cm/s, this was undertaken 7 times in a 30 week period for an MABR operated up to 330 days. The main disadvantage of these procedures is the decreased performance in the period immediately following biofilm removal. However, Brindle et al²² reported COD removal efficiency recovery within 0.5 to 2 HRT. Insufficient data has been reported on recovery times for other studies where membrane cleaning has been applied.

The configuration of the membrane module and the intensity and duration of air scour and liquid flushing procedures are clearly important parameters in determining the effectiveness of biomass control, however insufficient data is currently available to draw conclusions in this regard.

It is interesting to note that biomass control problems have not been reported in autotrophic based MABR trials employed for nitrogen removal³⁰⁻³³. Autotrophs have comparatively low growth rates and yield coefficients compared to heterotrophs and it seems likely that biofilm accumulation is more effectively balanced by erosion and biomass decay in such systems.

Effect of liquid flow velocity: hydrodynamics

Bulk liquid hydrodynamic conditions have been shown to influence biofilm density^{65 66}, the concentration boundary layer at the liquid-biofilm interface^{65 66 67}, the bulk liquid mixing⁶⁰, detachment rate⁶⁶ and the stratification of bacterial activity and community structure²⁹. The overall effect of hydrodynamic conditions on process performance in a biofilm reactor is complex and the interrelationships between hydrodynamic conditions and biofilm characteristics remains to be elucidated. Some progress has been made in this area of biofilm research by the application of spatially structured mathematical models^{68,69}, however, for MABRs such model have only been introduced quite recently⁷⁰ and have not yet been applied to the effect of hydrodynamics on process performance.

Prospects for full-scale implementation of MABR technology

Objective comparisons between the MABR and alternative processes are complicated by the extensive variety of reactor designs, membrane characteristics, operating conditions and wastewater characteristics that exist. Notwithstanding this difficulty, it is apparent that specific COD and nitrification rates obtained from preliminary MABR trials are consistently higher than many other wastewater treatment technologies. Although scale-up challenges remain, there appears to be three areas where the MABR can be expected to find greatest application; total nitrogen removal, high-rate treatment and high-strength COD removal.

The potential of the MABR for nitrogen removal

There are now a significant number of reports confirming the performance of the MABR as a technology that can achieve high rate nitrification and very high nitrogen removal percentages. Developments in the understanding and application of excess biomass amelioration methods are required before full-scale MABR installations can be considered for medium to high carbon to nitrogen (COD/N) ratios. However, for (COD/N) ratios, the potential exists for full scale implementation in the

short term, provided appropriate membrane modules become commercially available. An item of concern relates to the possibility of inhibition of ammonium oxidizing bacteria by high oxygen concentrations. There is some preliminary evidence to suggest, using side-by-side comparisons of air-fed versus oxygen-fed MABRS, that pure oxygen may have an inhibitory effect on nitrification. Osa et al⁵⁶ reported nitrogen removal rates of $47 \text{ g}_N\text{m}^{-2}\text{d}^{-1}$ and $11 \text{ g}_N\text{m}^{-2}\text{d}^{-1}$ with air and oxygen respectively. Cole et al²⁹ showed, using PCR-DGGE of 16S rRNA gene fragments that ammonia oxidizing genes were more prevalent in an air-fed versus oxygen fed MABR. Despite these observations, the performance data obtained from MABR trials, as summarized in Table 2, clearly confirm that high rate nitrification is achievable in MABRs, even with the use of pure oxygen. However, further experimental will be needed to investigate the influence of oxygen inhibition on performance.

The potential of the MABR for high rate treatment

Under optimized conditions it is evident, based on laboratory scale data, that the MABR has the potential to outperform several high-rate processes in current use, such as BAFs and MBBRs. It is important to highlight that the superior performance rates of the MABR can, in many cases, be attributed to the use of pure oxygen compared to air. However, a key benefit of the MABR is the high oxygen utilization efficiencies attainable which may confer an economic advantage in terms of aeration energy requirements. Because the energy requirements for aeration and mixing comprise a very significant fraction of the operating costs of aerobic biotreatment processes, the MABR has the potential to offer energy cost savings. This important aspect of MABR performance appraisal has, surprisingly, been scarcely dealt with in the open literature. Preliminary estimates of the energy requirements for prospective full scale MABR installations are summarised in Table 4 together with figures from comparable conventional technologies. Design assumptions are outlined in the supporting information of this article. Two cases were chosen for illustrative purposes; Case 1 is based on a published comparison⁵² between a hollow fibre MABR and a conventional activated sludge process (CAS) both designed for the treatment of a $3780 \text{ m}^3\text{d}^{-1}$ municipal wastewater stream. Case 2 is a comparison

between a pure oxygen MABR and an existing high-purity oxygen (HPO) activated-sludge system, both specified to treat $115,200 \text{ m}^3 \text{d}^{-1}$. Wastewater characteristics, loading rates, outline design parameters for both cases are detailed in the supporting information. Although full-scale data is still lacking, it appears that the energy required for aeration and mixing of full scale MABR can be expected to be in the region of $0.25 \text{ kWh/kgCOD}_{\text{removed}}$ this is approximately 3 to 4 times less energy intensive than the conventional AS process ($1.05 \text{ kWh/kgCOD}_{\text{removed}}$) or the BAF process (0.9 to $1.2 \text{ kWh/kgCOD}_{\text{removed}}$)¹. These findings are in agreement with the figures reported by Suzuki et al²⁴ who calculated that the total energy costs of an MABR to be less than 40% of a comparable activated sludge process. Despite the potential energy cost savings of the MABR it is, as-yet unclear if the MABR will become a cost effective technology, a key issue is the capital cost associated with membrane replacement. Significant research is still required before commercially viable membrane models for technical scale MABRs can be specified.

The potential of the MABR for high strength COD removal

Membrane-aerated biofilms supplied with pure oxygen are distinct from conventional aerated biofilms, because, for the same specific surface area of support, significantly higher biomass concentrations can be achieved in the MABR due to comparatively higher oxygen penetration depths. This opens up the possibility to treat wastewater of comparatively higher strength. There is evidence to show good removal efficiency at influent concentration of up to $2400 \text{ mgCOD L}^{-1}$ ²² and it should be possible to operate at higher feed concentrations provided membrane module design can be optimized to provide sufficient oxygenation⁷¹. For comparison purposes, it is useful to examine the limits of applicability of various treatment processes. Figure 3, which is adapted from Nicolella et al⁷² is a concentration flow rate phase diagram separating the range of applicability for several common biotreatment processes with emphasis on COD removal. The lines separating the different regions, labeled A to F, were defined using kinetic and physical parameters typically encountered in wastewater treatment⁷². Under optimized conditions, the potential exists for the MABR to find a niche as an aerobic technology for high strength

wastewater treatment, an application not normally associated with biofilm reactors, primarily as result of diffusional limitations.

As with any biofilm reactor, the biofilm thickness will have a significant effect on the total biomass concentration. Notwithstanding the difficulties in excess biofilm control, it is possible to estimate overall biomass concentrations as a function of biofilm thickness, membrane outer diameter and spacing in hollow fiber MABRs using straightforward geometric calculations as shown in Figure 4. Under the specified sample conditions, typical of wastewater treatment (see supporting information), diffusional limitations become apparent at a biofilm thickness of greater than 450 μm . Depending on the membrane dimensions, this would support overall biomass concentrations in the region of 10 kg m⁻³. Overall biomass concentrations are maximized when the membrane outer diameter is at the minimum. However, a compromise exists; thin membranes may not provide sufficient surface area for oxygenation of thick biofilms. Moreover, if pressurized oxygen is to be used there is an upper limit to the membrane wall thickness that provides sufficient strength but ensures an adequate lumen diameter.

It would appear, provided appropriate reactor design, operating conditions are chosen and biomass control issues are addressed, that the MABR can be expected find application as a biofilm technology for the treatment of comparatively high strength wastewater. At present, very few studies have applied the MABR to this application²² despite the apparent potential that exists.

Outlook and priorities for technology development

If the MABR is to achieve the potential indicated by laboratory scale trials, several technical challenges need to be overcome. The principal obstacle to full scale implementation is the problem of excess biomass control which can lead to significant performance deterioration. Many of the laboratory scale studies reported to-date operated with low membrane packing densities and thus, the problem of biomass control was not prioritized. Several biomass control strategies have been trialled with mixed success; however, there is currently a wholly inadequate understanding of biofilm detachment

mechanisms. Possible developments in this area are likely to focus on membrane material and module design improvements in conjunction with selection of appropriate liquid/gas scouring methodologies.

To-date, most MABR studies have used either commercially available microfiltration/ultrafiltration membrane modules, not specifically designed to support biofilm growth or have been developed *in-house* using commercially available materials such as silicone tubing. There is a clear need to design membrane modules specifically for MABRs if they are to be used at technical scale. Requirements for such membrane modules were outlined by Semmens⁵²; the membrane material must be sufficient robust and strong to support the weight of biomass and to be able to withstand damage during installation; the design should ensure that the gas-phase pressure drop is low and that gas distribution is uniform across the membrane; provision should be made for the removal of water due to condensation or leakage from the lumen; the membrane pores should not wet under the prevailing operational conditions; the membrane spacing should be sufficient for biofilm development and adequate liquid contact; provision should be made for excess biomass amelioration measures such as external bubble aeration; the membranes should have a low replacement cost and be suitable designed for large scale implementation.

Further development of the MABR may be stimulated by the availability of robust process and economic data that seeks to benchmark the technology against conventional biofilm processes. There is a need for pilot scale side-by side comparisons between the MABR and established processes using identical wastewater streams and comparable operating conditions. Pilot-scale studies should give prioritization to methods for amelioration of excess biomass, the effect of shock loads, the treatment performance with respect to suspended solids and to the investigation of the factors influencing membrane durability under conditions representative of real wastewater. In conjunction with pilot scale-studies, there is a need for the development of detailed and scalable process economic models of the MABR with particular emphasis on energy requirements, sludge production, pre-treatment requirements. A techno-economic model would form an important input into scale-up design strategies.

Improvements in MABR performance may also be gained by further exploration of non-continuous operation, such as sequencing batch MABRs^{41, 73-75}, or by novel hybrid designs that combine the MABR with other technologies³⁸⁻⁴². There is also a continuing need for basic research into fundamental mechanisms governing MABR performance. In particular, experimental examination of the spatial dynamics of the microbial population stratification under the influence of variable loading rates, presence of inhibitors and stochastic detachment events, should be undertaken. Advances in these areas will be facilitated by good experimental design and augmented by the use of a new generation of multispecies^{36, 76} and spatially-structured mathematical models⁷⁰. Ultimately, successful scale-up and optimisation of the MABR will rely on developing an improved understanding of the interrelationship between the various factors governing performance.

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SUPPORTING INFORMATION PARAGRAPH

Details on the generation of Figure 4 and the sources, assumptions and calculations for the data in Table 4 are included in the supporting information

FIGURE CAPTIONS

Figure 1 Schematic drawing showing the transport fluxes of soluble constituents and indicative microbial stratification in a membrane-aerated biofilm in contact with a typical wastewater. Solid lines indicate advective transport, dashed lines indicate diffusive transport. Transport in the biofilm matrix is indicated via diffusion only. The mass transfer resistances at the liquid-biofilm interface and the membrane are determined principally by the bulk liquid hydrodynamics and the membrane material and thickness respectively.

Figure 2 Interrelationships between various factors influencing process performance. Wastewater characteristics are implicit in this scheme.

Figure 3 Concentration flow rate phase diagram, adapted from Nicolella et al⁷². Regions are defined as follows. A: retention time so long that microorganisms grow in suspension. B: At high flowrates only static biofilms can be retained. C: loading conditions suitable for particulate biofilms systems (very high specific surface area) D: Conditions suitable for flocs provided separation and biomass recycle used. E: Concentration and flowrate suited to sludge bed reactors. F: flowrate too high for particulate and sludge bed systems, concentration too high for conventional biofilm reactors.

Figure 4. Effect of maximum design biofilm thickness on total biomass concentration (—) and specific surface area (----) in a hollow fibre MABR for 3 membrane diameters, a biofilm density of 30 kg m⁻³ and a minimum spacing of 0.5 mm between outer biofilm. For a typical specific oxygen utilization rate of 0.25 kg_{O2} kg_X⁻¹ hr⁻¹ and an intra-membrane oxygen pressure of 200kPa the actual biomass concentration available for oxidation is shown (····). All calculations are in the supporting information.

Reference	Total volume	Working volume	Membrane area	a	Membrane material and aeration mode	Q	HRT	COD in	COD loading (flux)	COD removal (flux)	COD loading (volumetric)	COD removal (volumetric)	Removal Efficiency
	L	L	m ²	m ² /m ³		L/hr	hr	mg/L	g/m ² day	g/m ² day	kg/m ³ day	kg/m ³ day	
19	1.345	0.86	6.87	5107	Polypropylene, HF, DE, O ₂	1.344	1.0	253	1.24	0.855	6.33	4.37	69
	1.345	0.86	6.87	5107		1.344	1.0	369	1.75	1.51	8.94	7.69	86
21	1.9	1.35	0.69	511	Polypropylene, HF, DE, O ₂	1.72	1.1	139	6.07	5.03	3.1	2.6	83
	1.9	1.35	0.69	511		1.71	0.80	1135	47.9	42.7	24.5	21.8	89
22	7.3	6.75	3.3	447	Composite, HF, DE, O ₂	0.73	10	1982	10.6	8.3	4.8	3.7	78
	7.3	6.75	3.3	447		4.06	1.8	2395	71.4	64.3	31.9	28.7	90
27	22.6	7	2.95	422	Polyethylene, HF, OE, O ₂	3.8	6	274	8.4	7.5	3.5	3.2	90
	22.6	7	2.95	422		3.8	6	394	12.1	10.9	5.1	4.6	90

Table 1 COD removal in MABR studies. Where various loading rate were applied the maximum and minimum steady-state removal rates are tabulated. Abbreviations: a: specific surface area of membrane, DE: dead-end lumen, OE: open ended lumen, HF: hollow fiber, Q: liquid flow rate.

Reference	Working volume	Area	a	HRT	Membrane material and aeration mode	Temperature	NH ₄ -N in	NH ₄ loading (flux)	NH ₄ -N removal (flux)	NH ₄ loading (volumetric)	NH ₄ -N removal (volumetric)	Removal efficiency
	L	m ²	m ² /m ³	hr		°C	mg/L	g/m ² day	g/m ² day	kg/m ³ day	kg/m ³ day	%
31	0.43	0.078	185	4	Polyethylene, HF, DE, oxygen	30	43	1.42	1.41	0.26	0.26	99.5
	0.43	0.078	185	1		30	52	6.87	6.84	1.27	1.27	99.6
77	100	1.96	19.6	10	PTFE, HF, OD: 4 mm, Air, OE	30	25.7	3.15	2.20	0.062	0.043	70
32	3	0.0471	16	8	Silicone, Spiral HF, OD 2.5mm, OE, oxygen	30	118-707	2.57	2.31	0.040	0.0036	90
17	0.15	.0075	50	360	Polyethylene HF, OD: 3mm, DE, air	25	3000	5.27	4.48	0.27	0.23	85
27	7	2.95	422	12	Polyethylene HF, DE, Air	NA	49	0.75	0.60	0.32	0.25	80
	7	2.95	422	6			87	2.66	2.40	1.12	1.01	90
28	4.5	0.25	56	53.3	Polyurethane, HF, OD: 0.28mm, O ₂	20	34	0.6	0.57	0.033	0.032	95
78	20	4	200	2	Silicone, Spiral, 0.63 bar O ₂	27	221	5	4.5	1.0	0.9	90
	20	4	200	2		27	221	75	35	15.0	7.0	47
34	0.86	0.25	290	3	Polyacrylonitrile, HF, OD: 1 mm up to 100kPa Air	25	100	0.44	0.44	0.13	0.13	100
	0.76	0.5	660	3		25	100	0.45	0.45	0.30	0.30	100
	0.63	0.7500	1190	4.5		25	100	0.44	0.43	0.62	0.60	97.7
79	0.9	0.18	45	8	Carbon, HF, OD: 8.9mm, 0.2 bar O ₂	30	100	11.92	9.3	0.54	0.42	78
42	3.25	0.13	40	6	Polyethylene, HF, OD: 0.28mm. Air at 70kPa	NA	20	1.95	1.65	0.078	0.066	85

Table 2. Nitrification application studies in MABRs. Abbreviations: a: specific surface area of membrane, DE: dead-end lumen, OE: open ended lumen, HF: hollow fiber, OD: outer diameter of membrane

	Reactor configuration	Membrane material	Aeration mode	Carbon source	Feed concentration	Removal rate	removal efficiency	HRT (h)
43	CSTR with immersed tubular membrane, stirrer mixed	Silicone	Air/oxygen	Xylene	275g _{COD} m ⁻³	1750g _{COD} m ⁻² day ⁻¹	50%	6
74	1 litre SSBR with immersed tubular membrane, magnetic stirrer mixed	Silicone	Oxygen	Phenols	90mg _{phenol} l ⁻¹	89 g _{phenol} m ⁻³ day ⁻¹	99%	24
65	single tube membrane reactor, continuous flow	Silicone	oxygen, 9 l hr ⁻¹	Xylene	210 mg _{COD} l ⁻¹	4.39 g _{COD} m ⁻³ day ⁻¹	98%	4.1
59	internal membrane/ external membrane module (with activated carbon) Continuous flow with internal recirculation	Silicone	Air/ Oxygen	Benzene, 2-chloro-phenol 2,4-dichloro-toluene	3.5g _(2cp, benzene) l ⁻¹	15 kg _{organics} m ⁻³ day ⁻¹	99%	6
80	CSTR with immersed tubular membrane, stirrer mixed	Silicone	Air, 8l hr ⁻¹	Xylene	207 mg _{COD} l ⁻¹	0.887 g _{COD} m ⁻³ day ⁻¹	90%	5
48	SSBR (external recycle), (CFBR once through) with immersed spiral wound tubular membrane	Silicone	Oxygen	Chlorophenol	8mg _{chlorophenol} l ⁻¹	32 g _{chlorophenol} m ⁻³ day ⁻¹	95%	6
47	SSBR with immersed membrane, stirrer mixed	Silicone	Oxygen	Phenols	120 mg _{phenol} l ⁻¹	126mg _{phenol} m ⁻² hr ⁻¹	99%	12
16	single tube membrane reactor, continuous flow with internal recirculation	Silicone	Methane/air	TCE	31.7 μmol l ⁻¹	28800mol m ⁻² day ⁻¹	80-90 %	26
49	SSBR (external recycle), (CFBR once through) with immersed spiral wound tubular membrane	Silicone	Oxygen	monochlorophenol	207 mg l ⁻¹	0.053 kg m ⁻³ day ⁻¹	95%	6
81	Dual compartment reactor with flat sheet membrane. Continuous flow with internal recirculation	Polypropylene	Air/ Oxygen (5ml min ⁻¹)	Perchloroethylene (PCE)	70 mg _{PCE} l ⁻¹	547mmol _{PCE} m ⁻³ h ⁻¹	99%	9

Table 3 Xenobiotic biotreatment application studies in MABRs

Table 4 Summary aeration/mixing energy requirements for prospective full scale MABRs compared to CAS (conventional activated sludge) and high-purity oxygen activated sludge systems (HPO-AS). Sources, assumptions and calculations are detailed in the supporting information.

	Case 1		Case 2	
	CAS	MABR	HPO-AS	MABR
Source	52	52	82	This study
Liquid flow rate (m ³ /hr)	158	158	4800	4800
COD influent concentration (mg/L)	475	475	317	317
Reactor volume (m ³)	950	950	9600	5760
Hydraulic retention time (hr)	6	6	2	1.2
Biomass concentration (g/L)	NA	NA	3000	5000
COD loading rate (g/m ³ d)	1900	1900	3800	6333
Total Aeration/mixing power (kW)	79 ^a	19 ^b	714	412 ^c
Specific aeration/mixing energy (kWh/kg _{COD})	1.05	0.25	0.53	0.31

Notes

a for the CAS power requirements were calculated assuming diffuser efficiency of 10%

b in the original publication⁵² no account was taken of liquid mixing, it is included here assuming a value of 20kW/1000 m³.

c energy requirements for liquid mixing assumes a value of 20kW/1000 m³

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