The status of membrane bioreactor technology

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In this article, the current status of membrane bioreactor (MBR) technology for wastewater treatment is reviewed. Fundamental facets of the MBR process and membrane and process configurations are outlined and the advantages and disadvantages over conventional suspended growth-based biotreatment are briefly identified. Key process design and operating parameters are defined and their significance explained. The interrelationships between these parameters are identified and their implications discussed, with particular reference to impacts on membrane surface fouling and channel clogging. In addition, current understanding of membrane surface fouling and identification of candidate foulants is appraised. Although much interest in this technology exists and its penetration of the market will probably increase significantly, there remains a lack of understanding of key process constraints such as membrane channel clogging, and of the science of membrane cleaning.

Introduction

Membrane bioreactor (MBR, see Glossary) technologies are, as the name suggests, those technologies that provide biological treatment with membrane separation. The term is more appropriately applied to processes in which there is a coupling of these two elements, rather than the sequential application of membrane separation downstream of classical biotreatment. Conventional treatment of municipal wastewater (sewage) usually proceeds through a three-stage process: sedimentation of gross solids in the feed water followed by aerobic degradation of the organic matter and then a second sedimentation process to remove the biomass (Figure 1). An MBR can displace the two physical separation processes by filtering the biomass through a membrane. As a result the product water quality is significantly higher than that generated by conventional treatment, obviating the need for a further tertiary disinfection process.

The commercial significance of this technology is considerable, with applications in municipal and industrial wastewater treatment becoming increasingly widespread. A recent review indicated the market value of MBR technology to be approximately US$217 million in 2005, rising at an average annual growth rate of 10.9% – significantly faster than other advanced wastewater treatment technologies (e.g. biological aerated filters and sequencing batch reactors), and also more rapidly than the markets for other types of membrane system*. Although originally commercialized in the early 1970s as a sidestream process (Figure 2a), it was the introduction of the immersed process (Figure 2b) twenty years later that precipitated exponential growth in both the number of installations and the total installed flow capacity of MBRs throughout the 1990s. The technology is becoming more cost-effective as membrane and membrane process costs continue to fall and environmental regulations become increasingly more stringent [1]. It is estimated that the market is currently doubling every seven years, and will be worth a projected US$360 million by 2010.

Process description

Process configurations

Several different process configurations exist for MBRs, including extractive and diffusive systems. In extractive systems the membrane is used to extract specific components across the membrane either for their discrete

Glossary

(e)EPS (extracted): extracellular polymeric substances.
Aerobic oxygen: dependent, as relating to degradation of organic matter.
Capex: capital expenditure.
CST: capillary suction time: an empirical measure of the filterability of sludge.
Dewaterable: ease with which water can be removed (from a sludge).
dMBR: diffusion MBR.
DOC: dissolved organic carbon.
eMBR: extraction MBR.
Floc: suspended solid particle of the mixed liquor.
Flux: volumetric flow rate per unit membrane area (e.g. L m^2 h^{-1}).
FS: flat sheet.
HF: hollow fibre.
HRT: hydraulic retention time: the time taken for the liquid phase to pass through a tank.
iMBR: immersed MBR.
MBR: membrane bioreactor.
Mixed liquor: the material formed in the bioreactor, containing biomass and other solids.
MLSS: mixed liquor suspended solids.
MT: multitube.
Opex: operating expenditure.
Permeability: flux per unit TMP.
rMBR: rejection MBR.
sMBR: sidestream MBR.
SMP: soluble microbial product.
SRF: specific resistance to filtration: a generic measure of filterability of a suspension.
SRT: solids retention time: the time taken for the solid (particulate) phase to pass through a tank.
SVI: sludge volume index: an empirical measure of the settlability of sludge.
TMP: transmembrane pressure (Pa).

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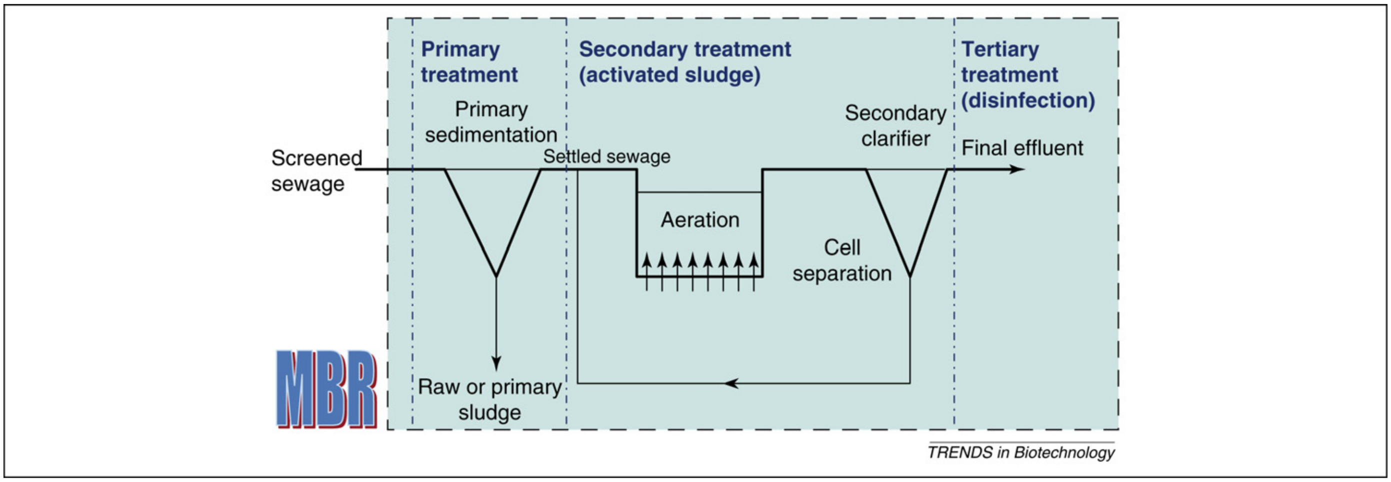

Figure 1. Schematic of conventional sewage treatment and unit operations displaced by MBR technology.

biotreatment or for biological treatment of the remaining effluent [2,3]. In diffusive MBRs the membrane is used to introduce gas into the bioreactor in the molecular form to enhance its use for biotreatment. This means that the gas is passed directly into the biofilm, formed directly on the membrane surface, without having to undergo dissolution. Therefore nearly100% utilization of the gas takes place, compared with ~30% for conventional air sparging.

The principal applications of MBR in biotreatment seem to be aerobic treatment at high loadings [4] and the more recent hydrogenation of oxyanions such as nitrate [5,6], which is conducive to treatment by all three configurations (Figure 3). However, notwithstanding the significant progress made in the development of diffusive systems in particular, extractive and diffusive systems have yet to be commercialized.

Rejection MBRs

Conventionally configured rejection MBRs (rMBRs, Figure 3b) combine biotreatment with membrane separation by microfiltration (MF) or ultrafiltration (UF), with the membrane being placed either external to or inside the bioreactor. The membranes are usually of flat sheet (FS) or hollow fibre (HF) configuration if placed inside the bioreactor, or multi-tube (MT) if placed outside it (Figure 4). The advantages offered by this process over conventional activated sludge processes (ASPs, Figure 1) are widely recognized [1], and of these the ones most often cited are:

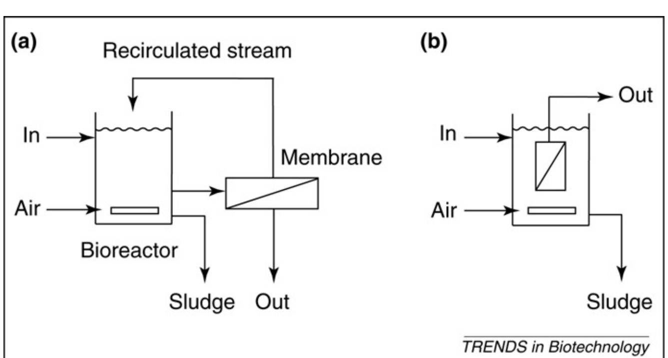

Figure 2. MBR process configurations: **(a)** sidestream and **(b)** immersed.

(i) Production of high quality, clarified and largely disinfected permeate product in a single stage; the membrane has an effective pore size <0.1 μm – significantly smaller than the pathogenic bacteria and viruses in the sludge.

(ii) Independent control of solids and hydraulic retention time (SRT and HRT, respectively). In a conventional ASP separation of solids is achieved by sedimentation, which then relies on growth of the mixed liquor solid particles (of flocs) to a sufficient size (>50 μm) to allow their removal by settlement. This then demands an appropriately long HRT for growth. In an MBR the particles need only be larger than the membrane pore size.

(iii) Operation at higher mixed liquor suspended solids (MLSS) concentrations, which reduces the required reactor size and promotes the development of specific nitrifying bacteria, thereby enhancing ammonia removal.

(iv) Reduced sludge production, which results from operation at long SRTs because the longer the solids are retained in the biotank the lower the waste solids (sludge) production.

Of these advantages, it is the intensity of the process (i.e. the smaller size of the plant compared to conventional treatment) and the superior quality of the treated product water that are generally most important in practical wastewater treatment applications. An MBR displaces three or four individual process, demanding only that the initial screening stage (which provides screened sewage from the raw sewage, Figure 1) be upgraded to limit the impact of large gross solids (>1–3 mm in size) on clogging of the membrane flow channels. Having said this, compared with conventional biotreatment processes MBRs are to some extent constrained, primarily by:

(i) Greater process complexity; membrane separation demands additional operational protocols relating to the maintenance of membrane cleanliness.

(ii) Higher capital equipment and operating costs; the membrane component of the MBR incurs a significant capital cost over and above that of an ASP and maintaining membrane cleanliness demands further

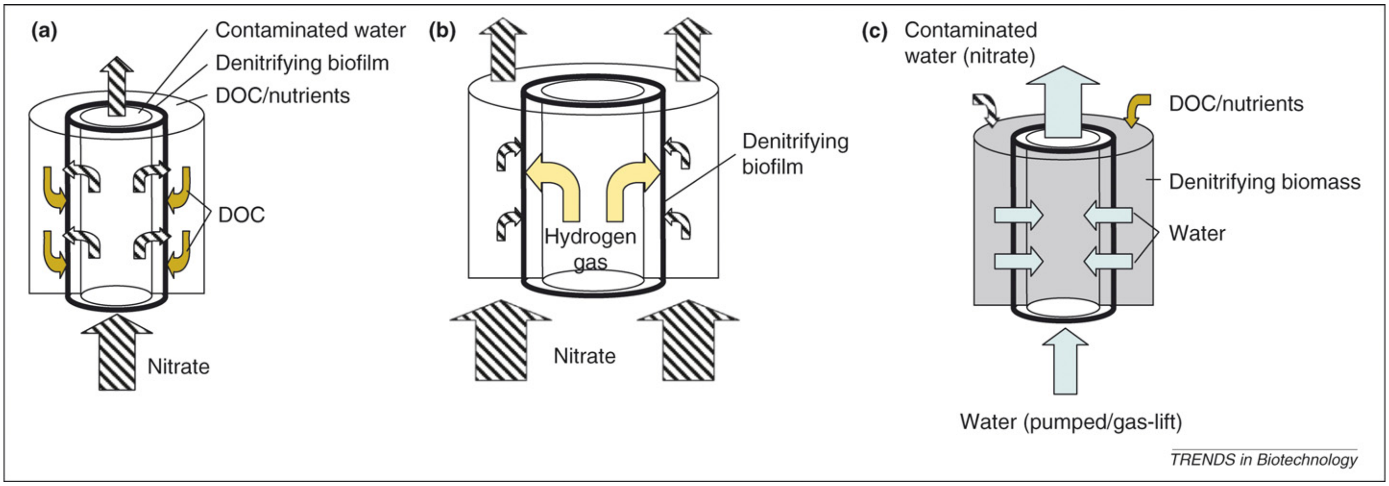

Figure 3. System configurations, denitrifying MBR: **(a)** nitrate extraction (eMBR), **(b)** membrane diffusion of hydrogen (dMBR) and **(c)** biomass rejection (rMBR).

capital equipment (capex) and operating costs (opex). This is only partly offset by the small size of the plant.

In addition, there are further operational issues, including greater foaming propensity (partly associated with the larger aeration demand of the MBR process compared with that of an ASP), a less readily dewaterable sludge product and generally greater sensitivity to shock loads.

Both these factors relate directly or indirectly to membrane surface fouling and membrane channel clogging. Fouling is the restriction, occlusion or blocking of membrane pores at the surface of the membrane, reducing the flow of permeate water through the membrane material. Channel clogging, sometimes referred to as sludging, is the filling of the channels between the membranes with sludge solids, restricting the flow of water over the membrane surface. Both fouling and clogging are ostensibly controlled by the system hydrodynamics and the application of cleaning protocols, but are also influenced by various design and operational facets of the MBR (Figure 5).

System parameter inter-relationships

As already stated, MBRs offer greater process control than conventional ASPs because of the uncoupling of SRT and HRT. These two parameters are usually defined by the system biokinetics (i.e. the speed at which the active microorganisms break down the components of the sewage in the MLSS). Long SRTs are usually desirable from a biokinetic standpoint because this produces more of the slower-growing microorganisms, as well as generating less sludge. Operation at long SRTs is made possible by the complete retention of the suspended solids by the membrane. HRTs can then be set according to the system microbiology and biokinetics: HRT and SRT are inter-related by the system biokinetics.

In selecting the best operating conditions, an appreciation of the impact of system design and operating parameters on each other is needed (Figure 5). Optimal design and operation of an MBR relies on effective treatment (i.e. removal of target contaminants) at the lowest overall cost. This then implies that the flux (volumetric flow rate per unit membrane area) of water through the

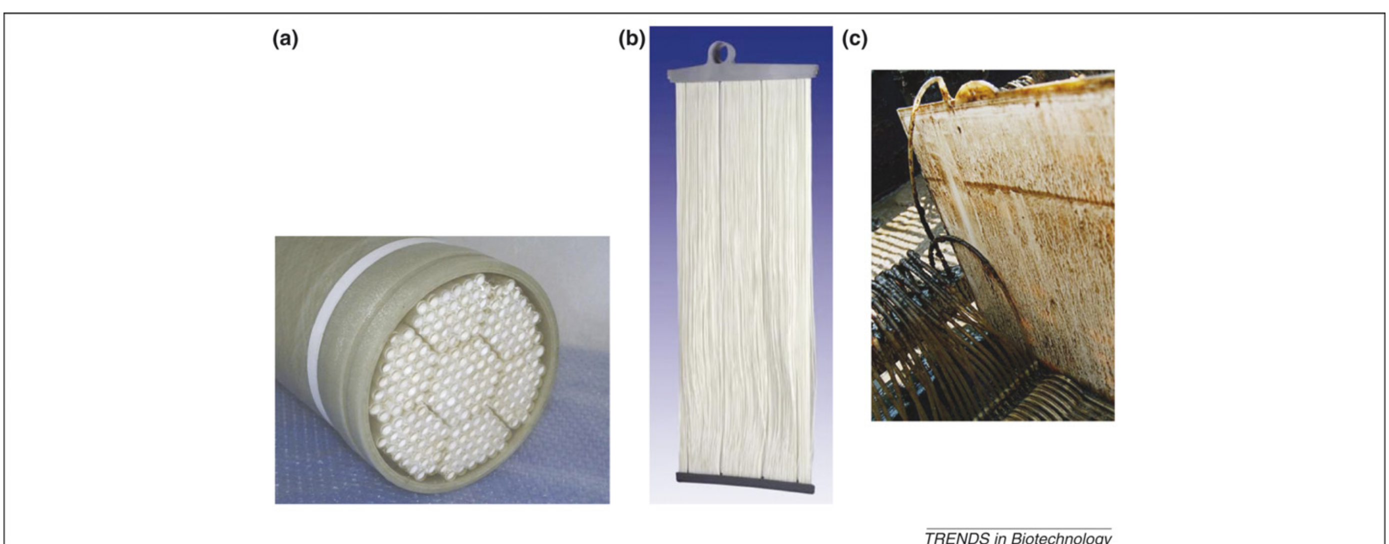

Figure 4. MBR membrane configurations: **(a)** multi-tube (MT), **(b)** hollow fibre (HF) and **(c)** flat sheet (FS). Adapted, with permission, from [1].

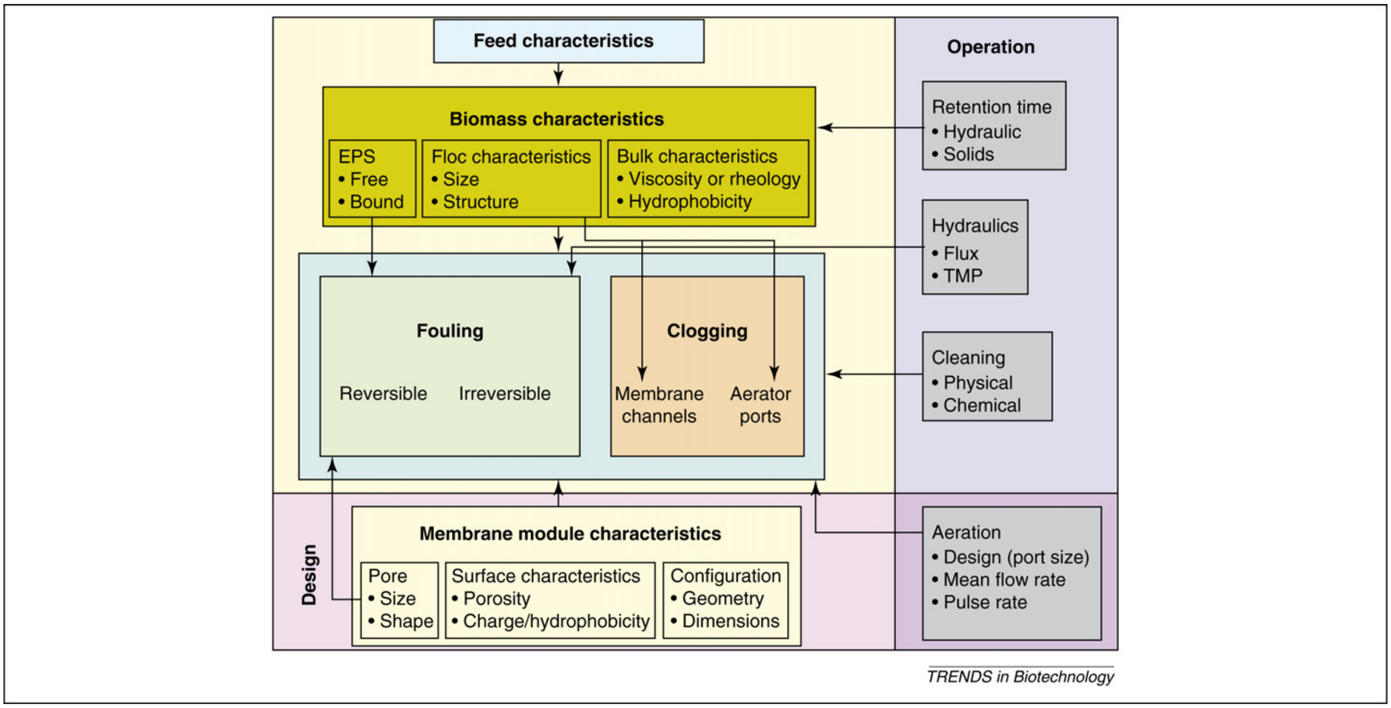

Figure 5. Inter-relationships between iMBR parameters and fouling. Adapted, with permission, from [1].

membrane must be maintained at as high a level as possible (i.e. the maximum suppression of fouling and clogging) with the minimum possible energy expenditure. Membrane fouling rate, the rate at which trans-membrane pressure (TMP) increases with time at constant flux, increases roughly exponentially with flux [7,8]. It is therefore desirable to operate at a low flux to maintain control of fouling and reduce opex, but this then incurs a higher capex because more membrane area is required.

Fouling that cannot be removed or suppressed by air scouring or other physical means (such as backflushing of the membrane by reversing the flow of water through it to dislodge the fouling layer) demands chemical cleaning. This uses aggressive chemicals such as oxidants (usually hypochlorite) to remove organic matter followed by organic acid (citric or organic acid) coupled with mineral acid to remove metal hydroxides. Membrane life data are limited, but anecdotal evidence suggests that membrane deterioration is accelerated by excessive cleaning with oxidative chemicals [9]. As with physical cleaning by air scouring, it is desirable to limit cleaning by operating at a lower flux, but this incurs a capex penalty.

For an iMBR (Figure 2b) membrane fouling is usually suppressed by the use of coarse-bubble aeration. These aerators produce large air bubbles through ports of >3 mm in diameter and when they are placed beneath the membrane module (normally HF or FS, Figure 4) the stream of air scours the membrane. The sustainable membrane permeability (i.e. the flux per unit TMP) increases roughly linearly with aeration rate for submerged FS and MT membranes [10–13], and similarly promotes permeation of HF membranes, although the relationship is more complex for this configuration.

Increasing the SRT increases the sludge solids (MLSS) concentration and thereby reduces the biotreatment tank size. However, the efficiency of oxygen transfer decreases exponentially with MLSS concentration [14,15]. Because biotreatment demands dissolution of oxygen into the biomass to allow aerobic degradation of the pollutants, a low oxygen transfer demands a higher aeration rate and a commensurately higher energy input.

It is therefore the case that several conditions for optimization are mutually counteractive. The classical opex–capex dichotomy prevails because low capex demands operation at:

(i) Higher sludge concentrations to enable use of smaller tanks and reduced waste sludge volume generation.
(ii) Higher fluxes to reduce membrane area demand.

Higher sludge concentrations increase energy demand, as well as increasing the risk of membrane clogging because of the deleterious impact on aeration efficiency of high sludge concentrations. Higher fluxes demand more frequent cleaning and/or more vigorous membrane aeration to maintain membrane permeability. In both cases, the result is an increase in opex. Conversely, shorter SRTs not only increase the sludge production but also decrease membrane permeability. This has been linked to increasing concentrations of foulant materials, and specifically soluble microbial product (SMP), with decreasing SRTs [16].

Two options for reducing energy demand in MBRs are (i) use of ceramic membranes and (ii) anaerobic operation. Ceramic membranes are more fouling-resistant but are currently high in cost, although recent advances in fabrication techniques could produce more economically

Table 1. Foulant definitions[a]

Practical definitions	Mechanism definitions	Foulant material type definitions
Reversible or temporary Removed by physical cleaning **Irreversible or permanent** Removed by chemical cleaning **Irrecoverable or absolute**[b] Not removed by any cleaning regime	**Pore blocking or filtration models** Complete blocking Standard blocking Intermediate blocking Cake filtration **Bespoke MBR fouling models defining sub-critical behaviour** Inhomogeneous fouling (area loss) Inhomogeneous fouling (pore loss) Inhomogeneous fibre bundle model Critical suction pressure Percolation theory	**Size** Molecular, macro-molecular, colloidal or particulate Surface charge and chemistry Positive or negative (cationic or anionic) **Chemical type** Inorganic (e.g. scalants) or organic (e.g. humic materials, EPS) Carbohydrate or protein (fractions of EPS) **Origin** Microbial (autochthonous), terrestrial (allochthonous) or man-made (anthropogenic) (Extracted) EPS [(e)EPS][c] or soluble microbial product (SMP) [1]

[a]Adapted, with permission, from [1].
[b]Irrecoverable fouling is long-term and insidious, and ultimately defines membrane life.
[c]eEPS refers to microbial products directly associated with the cell wall; SMP refers to microbial products not associated with the cell.

viable materials[†]. Recently there has been a resurgence of interest in submerged anaerobic MBRs [17,18][‡]. These might offer advantages over aerobic treatment because anaerobic operation demands no aeration and also generates methane, which can be used for energy generation. However, it is unclear as to whether coupling of an anaerobic process with a membrane offers significant advantages over conventional anaerobic technologies.

Foulant speciation and fouling control

Given its direct impact on opex, it is unsurprising that much research has been conducted on MBR membrane fouling, usually with a view to identifying those species primarily responsible for membrane fouling to enable suppression of their formation, rendering them innocuous or aiding their removal. Two types of foulant study dominate the MBR scientific literature: characterization and identification. Characterization refers to properties the foulant demonstrates either *in situ* (i.e. within the MBR, usually manifested as a decrease in permeability), or *ex situ* in some bespoke or standard measurement, such as capillary suction time (CST) or specific resistance to filtration (SRF). Identification refers to physical and/or chemical classification of the foulant, invariably through extraction and isolation before chemical analysis. Foulant isolates might also be characterized in the same way as the full mixed liquor.

In general, foulants can be defined in three different ways (Table 1):

(i) Practically, based on permeability recovery (the extent to which membrane permeability is recovered when different types of cleaning are applied to remove the foulants).
(ii) Mechanistically, based on fouling mechanism (the way in which the foulants interact with the membrane to reduce its permeability).
(iii) By material type (the chemical or physical nature or the origin of the foulant).

Of these, the practical definition for fouling is used almost universally and is important when considering membrane cleaning and its efficacy, although the actual science of membrane cleaning in municipal applications has received little attention. Reversible or temporary fouling is defined as fouling that is removed by physical cleaning, such as backflushing or relaxation (i.e. intermittently suspending permeation while continuing with membrane air scouring). Irreversible or permanent fouling is that which is removed only through the use of chemicals.

Fouling mechanisms take into account how the foulants deposit onto the surface or within the pores of the membrane. If it can be assumed that the mechanism does not change with time (i.e. the foulant deposition is not changed by existing foulant deposits), then filtration behaviour (the change of flux or TMP with time) can be predicted [19]. For fouling below the critical flux in MBRs more-specific models have been developed, largely by Fane and coworkers [20]. However, these fouling mechansistic models are thus far purely qualitative and are unable to predict fouling trends quantitatively.

The characterization of foulants has received much attention in the academic community. The bioreactor mixed liquor is generally fractionated on the basis of either physical size or chemical characteristics. Categorization by size has generally been into the three main groups of suspended solids, colloids and solutes. The solutes in the supernatant faction of mixed liquor have been further characterized according to their chemistry. Of key interest has been the nature of the origin of the autochthonous (i.e. microbial in origin) organic solutes, defined as extracellular polymeric substances or EPS, because these are widely recognized as being the group of compounds primarily responsible for fouling MBR membranes. These compounds are then divided into extracted EPS (eEPS), organic matter bound to the cell wall of the microorganism, or soluble microbial product (SMP), which is unbound (i.e. free) matter. From the mid-1990s onwards [21], many studies examining the impact of EPS on fouling have been conducted, and this has been the subject of recent reviews [20,22]. These have generally identified different and often conflicting trends in fouling as a function of candidate foulant species concentration.

[†] Bishop, B. *et al.*, Use of ceramic membranes in airlift membrane bioreactors, *8th International Conference on Inorganic Membranes (ICIM8), 2004 July 18–22, Cincinnati*.
[‡] Jefferson, B. *et al.*, Low temperature municipal sewage treatment with anaerobic MBRs, *The 6th International Membrane Science and Technology Conference: 2007 November 5–9; Sydney*.

The impact of the concentration of suspended solids on fouling has been investigated by several authors [11,23–26], and several studies of the impact of floc size have also been conducted [27,28]. Flocculant solids significantly impact on permeability because they are present at high concentrations, 8–18 g/L in most plants depending on the SRT, compared with 2.5–3.5 g/L for conventional ASP technology. Although it impacts on the operating flux, particulate matter on the membrane surface is readily removed by physical cleaning.

Studies based on size fractionation of the mixed liquor have generally demonstrated that it is the supernatant of the mixed liquor, and specifically the colloidal fraction, that provides the greatest permanent fouling propensity [28–32]. The relative contribution of the biomass supernatant to overall fouling ranges from 17% [28] to 81% [30]. However, quantitative comparison of results is difficult because these depend on the fractionation method used and there is currently no single agreed method. Moreover, such studies are generally limited to a narrow range of operating conditions (namely operating flux, HRT and SRT) and feedwater quality; the latter is known to profoundly impact on the fouling behaviour of the biomass [31].

EPS encompasses all classes of autochthonous macromolecules such as carbohydrates, proteins, nucleic acids, (phospho)lipids and other polymeric compounds found at or outside the cell surface and in the intercellular space of microbial aggregates – EPS are therefore extremely heterogenous. In some MBR membrane fouling studies the extracted EPS and SMP fractions have been analysed for their carbohydrate (or polysaccharide) and protein content. Correlations between fouling propensity and identified fractions of the supernatant mixed liquor have been produced, and specifically (but not exclusively) the carbohydrate component of the SMP [32–35] seems to promote fouling under some conditions. As with the process of EPS fractionation, the methods used for assaying carbohydrates and proteins are not universally agreed, and consequently different studies have identified different components with the highest fouling propensity. Evidence suggests that (at lower SRTs at least) it is the polysaccharide colloidal matter in the SMP that is primarily responsible for fouling [32] and this might explain the lower sustainable permeabilities attainable at lower SRTs reported by some authors [16]. For higher SRTs (>20 days), the most recent review of work in this area [36] concluded that fouling cannot be attributed to any one specific constituent of the mixed liquor.

Cleaning

As already stated, there have been few studies of the science of cleaning, although the optimization of cleaning protocols and their scheduling forms part of most pilot plant trials [37–41] (Table 2). The range of conditions chosen for physical and chemical cleaning of MBRs at full-scale is limited [1]. Physical cleaning, in the form of backflushing or relaxation, is applied for 1–2 min every 10–15 min. Chemical cleaning is mainly limited to alkaline (pH ~12) hypochlorite often followed by citric (or, occasionally, oxalic) acid at pH ~3. Chemical cleans using low-strength sodium hypochlorite are applied 2–8 times a month to maintain permeability, or 1–2 times a year using high-strength solutions to recover permeability. Variations exist between the FS and HF systems because FS operate at higher specific aeration demands and achieve commensurately higher sustainable permeabilities and therefore demand less cleaning.

Table 2. Membrane cleaning protocols

Cleaning schedule	Reagent	Frequency
Maintenance	100–500 mg/L sodium hypochlorite	Weekly to monthly
Recovery	0.3–0.5 wt % sodium hypochlorite	Quarterly to biennally

In-tank treatment, dosing with activated carbon [42,43] or proprietary reagents [44], have also been investigated. Although the apparent successful application of reagents for fouling suppression has been reported in short-term trials, the true benefit of using additives over extended periods remains unclear, given their cost and possible impact on residuals. However, additives could offer convenient temporary amelioration during periods of high hydraulic loading.

Running costs

Currently, two of the most significant components of MBR operation costs are membrane replacement and energy consumption and both relate to fouling[§]. There is insufficient information available about the impact of long-term operation on MBR membrane life-span, although anecdotal evidence suggests that most established commercial products are inherently robust: the plant at Porlock in the UK, installed in 1997, is still operating largely with the original membranes. However, there is also anecdotal evidence to suggest that extensive unscheduled membrane replacement has been necessary in many plants where maintenance of membranes has been insufficiently rigorous.

For an immersed MBR, ~30–50% of the energy demand arises from aeration of the membrane§ [1,40]. Membrane aeration is primarily responsible for promoting permeate flux and/or maintaining membrane permeability. A significant part of the operation cost therefore arises from the balance between the aeration imparted to the membrane (SAD_m, the specific aeration demand in m^3/h air per unit membrane area) and the net permeate flux flowing through it. The ratio of these two quantities yields a unitless parameter SAD_p, the ratio of volume of air applied per unit permeate volume attained. For a given aerator system at a fixed depth in the tank, SAD_p relates directly to specific energy demand for membrane aeration (E_A, in kWh per m^3 permeate).

In most full-scale immersed MBR installations currently in operation, SAD_p on average exceeds 10, and can be as high as 50 at some sites. Some recent studies have shown that the membrane aeration demand can be reduced to below 5 either by more intermittent application of air [40] or by redesigning the membrane module [41]. It

[§] Kennedy, S. and Churchouse, S.J., Progress in membrane bioreactors: new advances, *Water and Wastewater Europe Conference, 2005 June 28–30, Milan.*

remains to be seen whether operation at such low membrane aeration rates can be sustained over extended periods without leading to problems of fouling and clogging. Furthermore, the precise nature of the relationship between mode of aeration and membrane channel clogging is almost totally unexplored in reported MBR research, as is the nature of clogging of coarse bubble aerators. It is these relationships that are crucial in determining the required aeration rate, and thus the primary component of the energy demand.

A key issue regarding opex, however, is the selection of the most appropriate value of the flux. It is now generally accepted that for an MBR irreversible fouling always takes place – even at low flux values. There is a phenomenon in bench and pilot-scale studies where permeability catastrophically decreases after a certain period of continuous operation [45–47]. In full-scale plants this point is apparently never reached because maintenance cleaning is used to maintain permeability. The balance of flux and aeration rate remains a fundamental aspect of MBR technology design and operation.

Conclusions

Optimal operation of MBRs relies on an understanding of membrane fouling. There is currently no universally agreed constituent of the mixed liquor to which fouling can be primarily attributed. The most commonly identified component, the carbohydrate component of the soluble microbial product, seems to be an important foulant only at low SRTs.

The selection of operating parameter values is crucial. Conventionally MBRs have been operated at long SRTs to reduce sludge production. However, this impacts deleteriously on oxygen transfer for biotreatment, increasing aeration energy demand. Moreover, although correlation of permeability reduction with specific foulant species remains contentious, it is clear that extremely short SRTs are unlikely to be desirable both on opex and capex grounds. In practice, short SRTs tend to be favoured for the larger installations in which a sludge processing facility either already exists or is incorporated into the capital plan. On-site anaerobic digestion of the waste sludge provides an energy benefit at increased sludge yields and therefore at short SRTs. For sites with no on-site digestion faciltities operation is predominantly at longer SRTs to reduce sludge volumes and the associated tankering costs.

Future research in MBRs is likely to focus on reduction in energy demand through more frugal use of membrane aeration in immersed systems. This will rely on a better understanding of membrane channel clogging and chemical cleaning. The agglomeration of solids in membrane channels and coarse bubble aerators is a widely recognized problem in the operation of full-scale MBRs, but has received little attention from the academic community. Similarly, although ad hoc chemical cleaning strategies have been developed, the science of chemical cleaning is not well understood in MBRs. Advances in these areas will lead to more reliable and inexpensive biomass rejection MBR technologies in the future.

Finally, although currently only the biomass rejection MBR configuration is commercially-available, the development of alternative configurations should not be ignored. Low-energy processing of water and wastewater has led to exploration of coupling of bioreactors with other membrane separation processes, as well as to renewed interest in anaerobic MBR technologies. These technologies, which are potentially less energy-intensive than the biomass rejection technologies, could become more important in the future.

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