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Membrane Biological Reactors

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Abstract

Membrane biological reactors combine the use of biological processes and membrane technology to treat wastewater. The use of biological treatment can be traced back to the late nineteenth century. It became a standard method of wastewater treatment by the 1930s (Rittmann, 1987). Both aerobic and anaerobic biological treatment methods have been extensively used to treat domestic and industrial wastewater (Visvanathan et al., 2000). After removal of the soluble biodegradable matter in the biological process, any biomass formed needs to be separated from the liquid stream to produce the required effluent quality. In the conventional process, a secondary settling tank is used for such solid/liquid separation and this clarification is often the limiting factor in effluent quality (Benefield and Randall, 1980).

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4.16 Membrane Biological Reactors

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4.16.1 Introduction

Membrane biological reactors combine the use of biological processes and membrane technology to treat wastewater. The use of biological treatment can be traced back to the late nineteenth century. It became a standard method of wastewater treatment by the 1930s (Rittmann, 1987). Both aerobic and anaerobic biological treatment methods have been extensively used to treat domestic and industrial wastewater (Visvanathan *et al.*, 2000). After removal of the soluble biodegradable matter in the biological process, any biomass formed needs to be separated from the liquid stream to produce the required effluent quality. In the conventional process, a secondary settling tank is used for such solid/liquid separation and this clarification is often the limiting factor in effluent quality (Benefield and Randall, 1980).

Membrane filtration, on the other hand, denotes the separation process in which a membrane acts as a barrier between two phases. In water treatment, the membrane consists of a finely porous medium facilitating the transport of water and solutes through it (Ho and Sirkar, 1992). The separation spectrum for membranes, illustrated in **Figure 1**, ranges from reverse osmosis (RO) and nanofiltration (NF) for the removal of solutes, to ultrafiltration (UF) and microfiltration (MF) for the removal of fine particulates. MF and UF membranes are predominantly used in conjunction with biological reactors (Pearce, 2007). UF can remove the finest particles found in water supply, with the removal rating dependent upon the

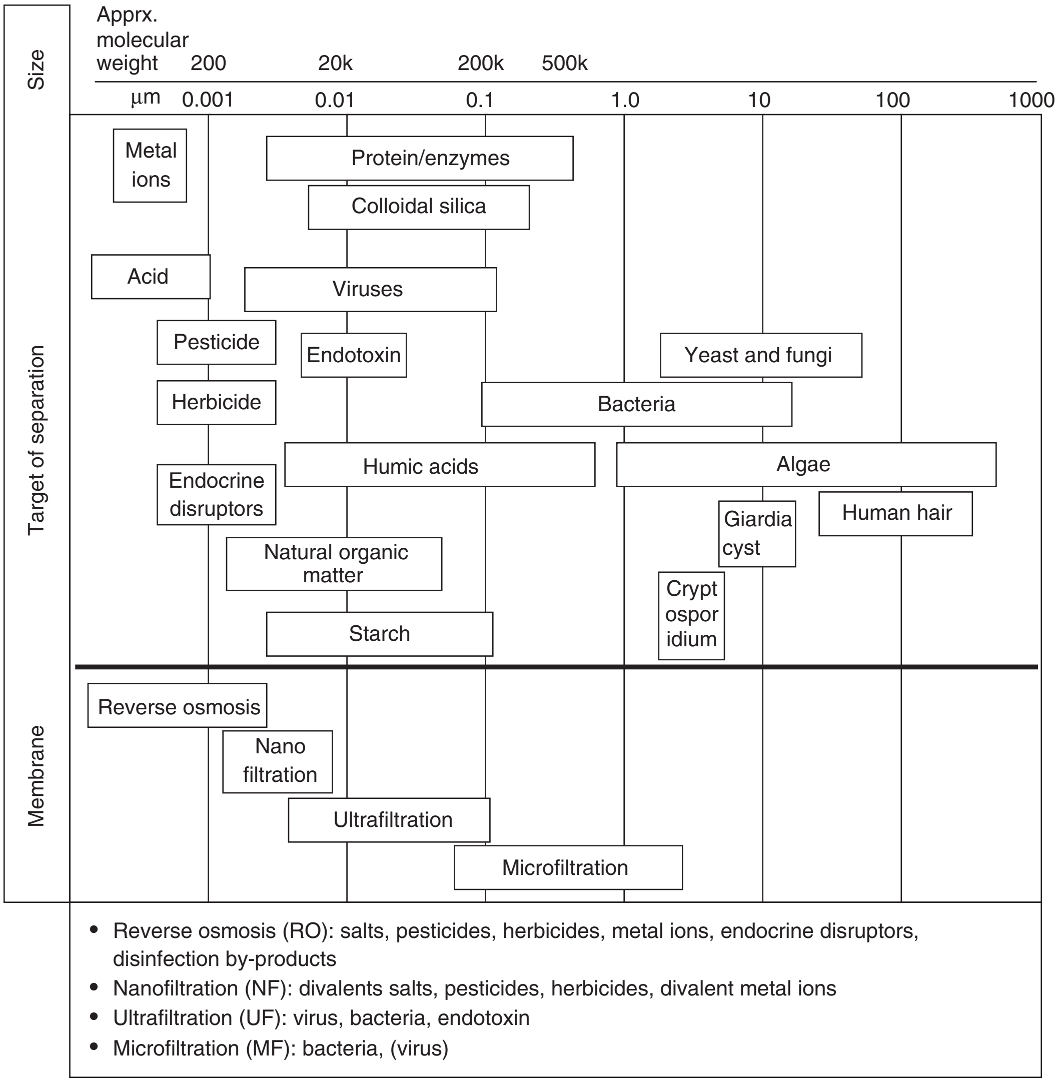


Figure 1 The separation spectrum for membranes.

pore size of the active layer of the membrane. The complete pore-size range for UF is approximately 0.001–0.02 µm, with a typical removal capability of UF for water and wastewater treatment of 0.01–0.02 µm. MF typically operates at a particle size that is up to an order of magnitude coarser than this. In water treatment, the modern trend is to use a relatively tight MF with a pore size of approximately 0.04–0.1 µm, whereas wastewater normally uses a slightly more open MF with a pore size of 0.1–0.4 µm (though wastewater can be treated using UF membranes, or MF membranes used for water applications). The market drivers for membranes in wastewater are illustrated in Figure 2. However, as in any separation process, in membrane technology too, the management and disposal of concentrate is a significant issue. Environment-friendly management and disposal of the resulting concentrates at an affordable cost is a significant challenge to water and wastewater utilities and industry.

To eradicate the respective disadvantages of the individual technologies, the biological process can be integrated with membrane technology. Although some recent studies have demonstrated case-specific feasibility of direct UF of raw sewage (Janssen *et al.*, 2008), membranes by themselves are seldom used to filter untreated wastewater, since fouling prevents the establishment of steady-state conditions and because water recovery is very low (Schrader *et al.*, 2005; Fuchs *et al.*, 2005; Judd and Jefferson, 2003). However, membrane filtration can be efficiently used in combination with a biological process. The biological process converts dissolved organic matter into suspended biomass, reducing membrane fouling and allowing increase in recovery. On the other hand, in the membrane filtration process, the membranes introduced into the bioreactors not only replace the settling unit for solid–liquid separation but also form an absolute barrier to solids and bacteria and retain them in the process tank.

As our understanding of membrane technology grows, we learn that membrane technology is now being applied to a wider range of industrial applications and is used in many new forms for wastewater treatment. Combining membrane technology with biological reactors for the treatment of municipal and industrial wastewaters has led to the development of three generic membrane processes within bioreactors (Figure 3): for separation and recycle of solids (Visvanathan *et al.*, 2000); for bubble-less aeration of the bioreactor (Brindle and Stephenson, 1996); and for extraction of priority organic pollutants from hostile industrial wastewaters (Stephenson *et al.*, 2000). There are other forms of membrane biological reactors such as enzymatic membrane bioreactor (Charcosset, 2006) for production of drugs, vitamins, etc., or membrane biological reactors for waste-gas treatment (Reij *et al.*, 1998), a discussion about which is beyond the scope of this chapter.

Solid–liquid membrane-separation bioreactors employ UF or MF modules for the retention of biomass to be recycled into the bioreactor. Gas-permeable membranes are used to provide bubble-less oxygen mass transfer to degradative bacteria

Criteria	Discharge	Reuse
Advantages	• Easily meets regulatory levels • Suitable for discharge to pristine environment	• Meets standards for potable applications • Increased value for industrial applications • May be useful in obtaining development permit

Figure 2 Market drivers for membranes in wastewater. Information from Howell JA (2004) Future of membranes and membrane reactors in green technologies and for water reuse. *Desalination* 162: 1–11; and Pearce G (2007) Introduction to membranes: Filtration for water and wastewater treatment. *Filtration and Separation* 44(2): 24–27.

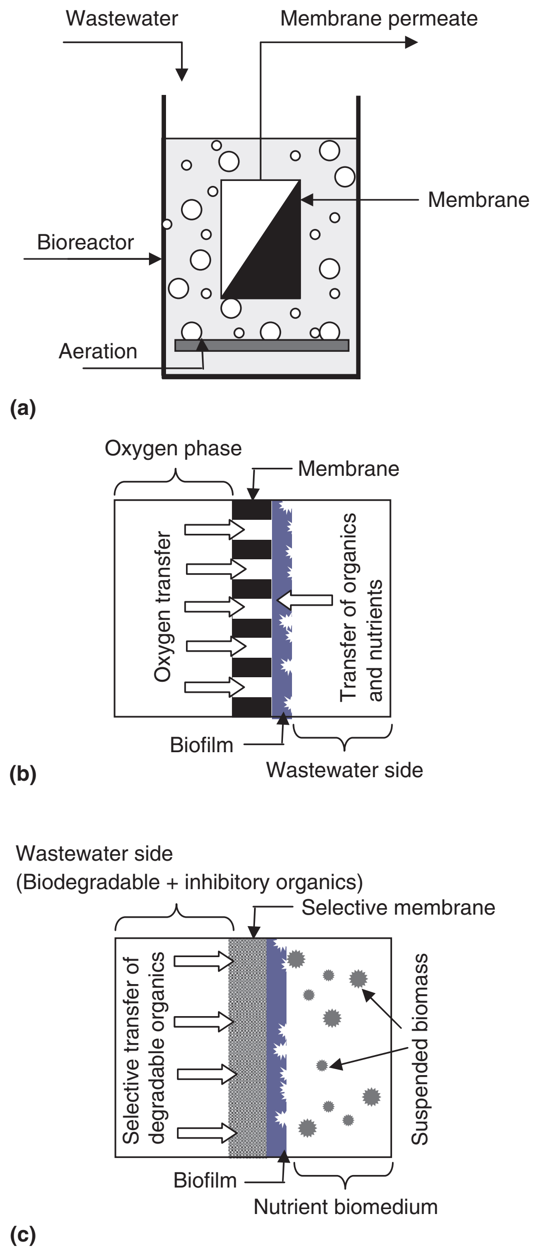


Figure 3 Simplified representation of membrane biological reactors: (a) biosolid separation, (b) aeration, and (c) extractive membrane biological reactors.

present in the bioreactor. Additionally, the membrane can act as support for biofilm development, with direct oxygen transfer through the membrane wall in one direction and nutrient diffusion from the bulk liquid phase into the biofilm in the other direction. An extractive membrane process has been devised for the transfer of degradable organic pollutants from hostile industrial wastewaters, via a nonporous silicone membrane, to a nutrient medium for subsequent biodegradation.

Biosolid separation is, however, the most widely studied process and has found full-scale applications in many countries. In a comprehensive review published in 2006, Yang *et al.* (2006) pointed out that the vast majority of research on membrane biological reactors since 1990 focused on biosolid-separation-type applications. There was no significant increase in the number of studies on gas diffusion and extractive membrane biological reactors over time. Publications on extractive and diffusive membrane biological reactors became available during 1994–95, after which a steady output of less than five publications a year was observed. This indicates that current research is predominantly in the water and wastewater-filtration area, in parallel with the commercial success in this field. In line with the current trend of research and commercial application, this chapter focuses on the biosolid-separation membrane biological reactors, which is more commonly known as membrane bioreactor (MBR). However, a brief outline of the other two types of membrane biological reactors is furnished in Section 4.16.2. The remainder of this chapter elaborates on the history, fundamentals, research and development challenges, as well as the commercial application of the biosolid-separation membrane biological reactors, which are henceforth referred to as MBRs.

4.16.2 Aeration and Extractive Membrane Biological Reactors

4.16.2.1 Aeration Membrane Biological Reactor

Wastewater-treatment processes using high-purity oxygen have a greater volumetric degradation capacity compared to the conventional air-aeration process. However, conventional oxygenation devices have high power requirements associated with the need for high mixing rate, and cannot be used in conjunction with biofilm processes. In the membrane-aeration biological reactors (MABRs), the capability of biofilm to retain high concentrations of active bacteria is coupled with the high oxygen transfer rate to the biofilm.

The key characteristic advantages of MABRs are summarized as follows:

- High oxygen transfer rate, especially suitable for high-oxygen-demanding wastewaters.
- In conventional aerobic biological wastewater treatment, volatile organic compounds (VOCs) can escape to the atmosphere without being biodegraded as a result of air bubbles stripping out the compounds from the bulk liquid. Since no oxygen bubbles are formed in MABRs, gas stripping of VOCs and foaming due to the presence of surfactants can be prevented (Rothemund *et al.*, 1994; Semmens 1991; Wilderer *et al.*, 1985) to a greater extent.
- Membrane-attached biofilms are in intimate contact with the oxygen source, with direct interfacial transfer and utilization of oxygen within the biofilm. In contrast to conventional biofilm processes, in MABR biofilms, oxygen from the membrane and pollutant substrate(s) from the bulk liquid are transferred across the biofilm in countercurrent directions (**Figure 4**). Biofilm stratification in MABRs results from this distribution of the maximum oxygen and pollutant-substrate concentrations at different locations within the biofilm and the relative thickness of MABR biofilms; this enables the removal of more than one pollutant type. The high oxygen concentrations coupled with the low organic carbon concentrations near the membrane/biofilm interface encourage nitrification, an aerobic heterotrophic layer above this facilitates organic carbon oxidation, and an anoxic layer near the biofilm/liquid interface supports denitrification (Stephenson *et al.*, 2000).

MABRs have been used to treat a variety of wastewater types at the laboratory scale (Brindle and Stephenson, 1996). However, in line with the characteristics of MABRs discussed above, most investigations show that the process is particularly suitable for the treatment of high-oxygen-demanding wastewaters, biodegradation of VOCs, combined nitrification, denitrification, and/or organic carbon oxidation in a single biofilm.

Bubble-less oxygen mass transfer can be accomplished using gas-permeable dense membranes or hydrophobic microporous membranes (Cote *et al.*, 1988). Both plate and frame and hollow-fiber membrane configurations have been used to supply the oxygen. Oxygen diffusion through dense membrane material can be achieved at high gas pressures without bubble formation. In hydrophobic microporous membranes, the pores remain gas filled; and oxygen is transported to the shell side of the membrane through the pores by gaseous diffusion or Knudsen flow-transport mechanisms. The partial pressure of the gas is kept below the bubble point to ensure the bubble-less supply of oxygen (Ahmed and Semmens, 1992; Rothemund *et al.*, 1994; Semmens, 1991; Semmens and Gantzer, 1993). Pressurized hollow fibers have been investigated in the dead-end and flow-through modes of operation. The evacuation of carbon dioxide from the bioreactor is a benefit of flow-through operation, though no quantitative work to determine removal rates has been undertaken (Cote *et al.*, 1997; Kniebusch *et al.*, 1990). Dead-end operation has usually been avoided, due to significantly decreased performance and condensate formation in the lumen (Cote *et al.*, 1997). The nonbiological fouling and loss of performance of dead-end porous hollow fibers due to iron oxidation, absorption of free oils and greases into pores, surfactants, and suspended solids, and fiber tangling have been reported (Semmens and Gantzer, 1993). Chemical treatment of the dead ends of these hollow fibers may provide a means for the condensate to escape.

The liquid boundary layer normally has a greater impact upon the overall oxygen mass transfer than the membrane, with mixing of the liquid a key operational parameter (Cote *et al.*, 1997; Kniebusch *et al.*, 1990; Wilderer *et al.*, 1985). However, wall thickness significantly affects the transport of

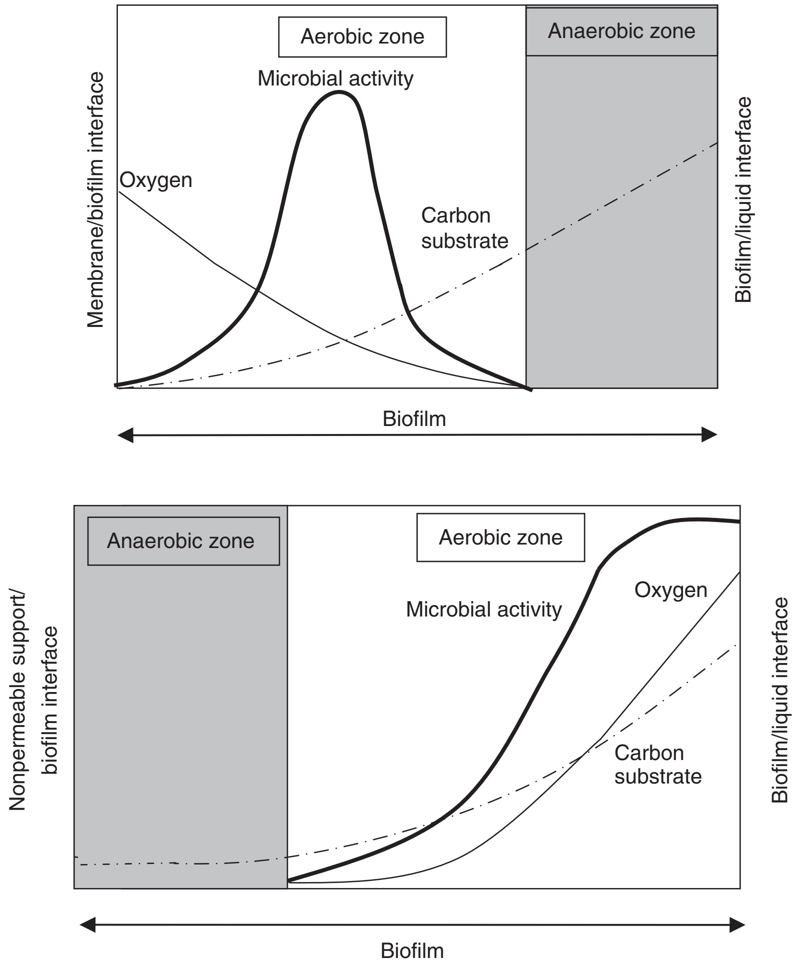


Figure 4 Simplified representation of the steady-state concentration profiles of oxygen, carbon substrate, and microbial activity in case of MABR biofilm and conventional biofilm.

oxygen through dense polymer membranes (Wilderer *et al.*, 1985). Oxygen transport is also controlled by the presence of membrane-attached biofilm and its thickness; the partial pressure of oxygen and flow-velocity characteristics on the lumen side; and the wastewater flow-velocity characteristics on the shell side of the membrane (Kniebusch *et al.*, 1990; Pankania *et al.*, 1994). Oxygen partial pressure provides the means for controlling the depth of oxygen penetration into the wastewater, with an increase in partial pressure resulting in an increase in the metabolic activity of the membrane-attached biofilm (Rothemund *et al.*, 1994). In bioreactors, most membranes used for oxygen mass transfer operate with the biofilm attached to the membrane surface. These biofilms are in intimate contact with the oxygen source and are protected against abrasion and grazing (Kniebusch *et al.*, 1990; Rothemund *et al.*, 1994). Scanning electron micrographs show that some attached bacteria inhabit the membrane pores, with the location of the oxygen and wastewater interphase very close to the bacteria (Rothemund *et al.*, 1994). Thus, oxygen-transfer resistance due to the thickness of the porous membrane and the liquid boundary layer are not necessarily decisive limiting factors (Kniebusch *et al.*, 1990; Rothemund *et al.*, 1994; Wilderer *et al.*, 1985).

Excessive biofilm accumulation can result in the transport limitation of oxygen and nutrients, plugging of membrane fibers, a decline in biomass activity, metabolite accumulation deep within the biofilm, and the channeling of flow in the bioreactor such that steady-state conditions may not be maintained (Debus and Wanner, 1992; Pankania *et al.*, 1994; Yeh and Jenkins, 1978). To operate at maximum efficiency, occasional membrane washing, air scouring, backwashes, and high recirculation rate of wastewater to achieve high shear velocities have all been employed to control biomass accumulation.

In the MABR process, oxygen is transferred without forming bubbles and therefore cannot be utilized to mix the bulk liquid. In laboratory scale MABRs, liquid-phase mixing has been achieved using recirculation pumps, impellers, magnetic stirrers, nitrogen, or air sparging.

4.16.2.2 Extractive Membrane Biological Reactor

The extractive membrane biological reactor (EMBR) process enables the transfer of degradable organic pollutants from hostile industrial wastewaters, via a dense silicone membrane,

to a nutrient medium for subsequent degradation (Brindle and Stephenson, 1996).

Membranes used for the extraction of pollutants into a bioreactor have been developed using pervaporation by exchanging the vacuum phase with a nutrient biomedium phase where biodegradation mechanisms maintain the concentration gradient needed to transfer organic pollutants present in hostile industrial wastewaters (Lipski and Cote, 1990; Nguyen and Nobe, 1987; Yun *et al.*, 1992). The inorganic composition of the nutrient medium is unaffected by the industrial wastewater within the hydrophobic hollow-fiber membrane. Hence, the conditions within the bioreactor can be optimized to ensure high biodegradation rate (Brookes and Livingston, 1993; Livingston, 1993, 1994).

The extraction and biodegradation of toxic volatile organic pollutants, such as chloroethanes, chlorobenzenes, chloroanilines, and toluene from hostile industrial wastewaters, with high salinity and extremes of pH, using EMBRs have been demonstrated at the laboratory scale (Stephenson *et al.*, 2000).

Further information on these two generic types of MBRs can be derived from the review papers by Brindle and Stephenson (1996) and McAdam and Judd (2006), and the book by Stephenson *et al.* (2000).

Yang *et al.* (2006) argued that extractive or aeration MBRs present a significant opportunity for researchers as niche areas of application as these novel processes remain unexplored. Hazardous waste treatment and toxic waste cleanup present two potential areas for the EMBR (Brookes and Livingston, 1994; Dossantos and Livingston, 1995; Livingston *et al.*, 1998), whereas hydrogenotrophic denitrification of groundwater (Clapp *et al.*, 1999; Mo *et al.*, 2005; Modin *et al.*, 2008; Nuhoglu *et al.*, 2002; Rezania *et al.*, 2005) and gas-extraction-assisted fermentation (Daubert *et al.*, 2003; Lu *et al.*, 1999) are potential research areas for the AMBR. It is also important to recognize the fact that these three membrane processes are not mutually exclusive and, if necessary, could be coupled into one bioreactor (Brindle and Stephenson, 1996). Once the research field has gained momentum, commercial interest might correspondingly follow.

4.16.3 History and Fundamentals of Biosolid Separation MBR

4.16.3.1 Historical Development

Membranes have been finding wide application in water and wastewater treatment ever since the early 1960s when Loeb and Sourirajan invented an asymmetric cellulose acetate membrane for RO (Visvanathan *et al.*, 2000). Many combinations of membrane solid/liquid separators in biological treatment processes have been studied since. The first descriptions of the MBR technology date from the late 1960s. The trends that led to the development of today's MBR are depicted in **Figure 5**. When the need for wastewater reuse first arose, the conventional approach was to use advanced treatment processes. The progress of membrane manufacturing technology and its applications could lead to the eventual replacement of tertiary treatment steps by MF or UF (**Figure 5(a)**). Parallel to this development, MF or UF was used for solid/liquid separation in the biological treatment process and thereby sedimentation step could be eliminated (**Figure 5(b)**). The original process was introduced by Dorr-Olivier Inc. and combined the use of an activated sludge bioreactor with a cross-flow membrane-filtration loop (Smith *et al.*, 1969). By pumping the mixed liquor at a high pressure into the membrane unit, the permeate passes through the membrane and the concentrate is returned to the bioreactor (Hardt *et al.*, 1970; Arika *et al.*, 1966; Krauth and Staab, 1988; Muller *et al.*, 1995). The flat-sheet membranes used in this process were polymeric and featured pore size ranging from 0.003 to 0.01 μm (Enegess *et al.*, 2003). Although the idea of replacing the settling tank of the conventional activated sludge (CAS) process was attractive, it was difficult to justify the use of such a process because of the high cost of membranes, low economic value of the product (tertiary effluent), and the potential rapid loss of performance due to fouling. Due to the poor economics of the first-generation MBRs, apart from a few examples such as installations at the basement level of skyscrapers in Tokyo, Japan, for wastewater reuse in flushing toilets, they usually found applications only in niche areas with special needs such as isolated trailer parks or ski resorts.

The breakthrough for the MBRs occurred in 1989, the process involved submerging the membranes in the reactor itself and withdrawing the treated water through the membranes (Yamamoto *et al.*, 1989; Kayawake *et al.*, 1991; Chiemchaisri *et al.*, 1993; Visvanathan *et al.*, 1997). In this development, membranes were suspended in the reactor above the air diffusers (**Figure 5(c)**). The diffusers provided the oxygen necessary for treatment to take place and scour the surface of the membrane to remove deposited solids.

There have been other parallel attempts to save energy in membrane-coupled bioreactors. In this regard, the use of jet aeration in the bioreactor was investigated (Yamagiwa *et al.*, 1991). The main feature of this process was that the membrane module was incorporated into the liquid recirculation line for the formation of the liquid jet such that aeration and filtration could be accomplished using only a single pump. Jet aeration works on the principle that a liquid jet, after passing through a gas layer, plunges into a liquid bath entraining a considerable amount of air. Using only one pump makes it mechanically simpler and therefore useful to small communities. The limited amount of oxygen transfer possible with this technique, however, restricts this process only to such small-scale applications. The invention of air-backwashing techniques for membrane declogging led to the development of using the membrane itself as both clarifier and air diffuser (Parameshwaran and Visvanathan, 1998). In this approach, two sets of membrane modules are submerged in the aeration tank. While the permeate was extracted through one of the sets, the other set was supplied with compressed air for backwashing. The cycle was repeated alternatively, and there was a continuous airflow into the aeration tank, which was sufficient to aerate the mixed liquor.

Eventually, two broad trends have emerged in recent times, namely submerged MBRs and sidestream MBRs. Submerged technologies tend to be more cost effective for larger-scale lower-strength applications, and sidestream technologies are favored for smaller-scale higher-strength applications. The sidestream MBR envelope has been extended in recent years by the development of the air-lift concept, which

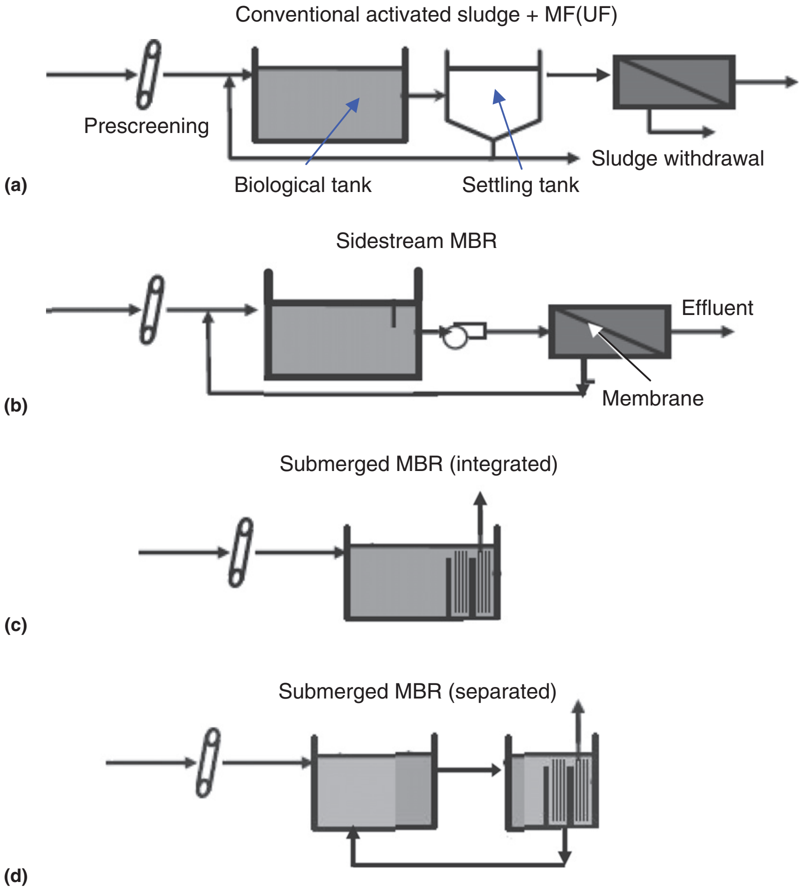


Figure 5 Evolution of membrane use in conjunction with bioreactor.

bridges the gap between submerged and cross-flow sidestream MBR, and may have the potential to challenge submerged systems in larger-scale applications (Pearce, 2008b). The economic viability of the current generation of MBRs depends on the achievable permeate flux, mainly controlled by effective fouling control with modest energy input (typically $\leq 1\,kW\,h^{-1}\,m^{-3}$ product). More efficient fouling-mitigation methods can be implemented only when the phenomena occurring at the membrane surface are fully understood. Detailed discussion on the technology bottlenecks and the design aspects are provided in Sections 4.16.4 and 4.16.5, respectively.

It is worth noting that as the oxygen supply limits maximum mixed-liquor suspended solids (MLSSs) in aerobic MBR, anaerobic MBRs (AnMBRs) were also developed. The first test of the concept of using membrane filtration with anaerobic treatment of wastewater appears to have been reported by Grethlein (1978). The first commercially available AnMBR was developed by Dorr-Oliver in the early 1980s for high-strength whey-processing wastewater treatment. The process, however, was not applied at full scale, possibly due to high membrane costs (Sutton *et al.*, 1983). The Ministry of International Trade and Industry (MITI), Japan, launched a 6-year research and development (R&D) project named Aqua-Renaissance '90 in 1985 with the particular objective of developing energy-saving and smaller footprint water-treatment processes utilizing sidestream AnMBR to produce reusable water from industrial wastewater and sewage. However, a high cross-flow velocity and frequent physicochemical cleaning was required to maintain the performance of such a high-rate MBR (Yamamoto, 2009). It was difficult to reduce the energy consumption significantly by adopting the sidestream operation using a big recirculation pump. On the other hand, commencing in 1987, a system known as anaerobic digestion ultrafiltration (ADUF) was developed in South Africa for industrial wastewater treatment (Ross *et al.*, 1992). This process is currently in operation. Further details on AnMBRs can be derived from the comprehensive review by Liao *et al.* (2006). This chapter, however, focuses on aerobic MBRs.

4.16.3.2 Process Comparison with Conventional Activated Sludge Process

Some important basic characteristics of CAS and MBR are compared in this section.

4.16.3.2.1 Treatment efficiency/removal capacity

The MBR process involves a suspended growth-activated sludge system that utilizes microporous membranes for solid/liquid separation in lieu of secondary clarifiers. The biological treatment in MBR is performed according to the principles

known from activated sludge treatment. However, higher suspended solids, biological oxygen demand (BOD), and chemical oxygen demand (COD) removals in MBR have been reported throughout the literature. With CAS, the colloidal fraction (that represents about 20% of the organic content of wastewater) has a residence time (hydraulic residence time (HRT)) in the range of few hours while with MBR, due to total SS retention, the residence time of this fraction (sludge retention time (SRT)) is in the range of several days. Thus, the biodegradation for this fraction is higher in MBR than in CAS. Some soluble compounds too, after being adsorbed on SS, can be retained in MBR and can be biodegraded to a better extent. Thus, some studies have ascribed the better removal of soluble COD in MBR to the fact that the effluent is particle free (Cote *et al.*, 1997; Engelhardt *et al.*, 1998; De Wilde *et al.*, 2003).

MBR produces quality effluent suitable for reuse applications or as a high-quality feedwater source for RO treatment. Indicative output quality includes suspended solids $<1\,mg\,l^{-1}$, turbidity <0.2 nephelometric turbidity unit (NTU), and up to 4 log removal of virus (depending on the membrane nominal pore size). In addition, it provides a barrier to certain chlorine-resistant pathogens such as Cryptosporidium and Giardia. In comparison to the CAS process, which typically achieves 95%, COD removal can be increased to 96–99% in MBRs (Stephenson *et al.*, 2000). Nutrient removal is one of the main concerns in modern wastewater treatment especially in areas that are sensitive to eutrophication. As in the CAS, currently, the most widely applied technology for N removal from municipal wastewater is nitrification combined with denitrification. Total nitrogen removal through the inclusion of an anoxic zone is possible in MBR systems. Besides phosphorus precipitation, enhanced biological phosphorus removal (EBPR) can be implemented, which requires an additional anaerobic process step. Some characteristics of MBR technology render EBPR in combination with post-denitrification as an attractive alternative that achieves very low nutrient effluent concentrations (Drews *et al.*, 2005b).

4.16.3.2.2 Sludge properties and composition

The presence of a membrane for sludge separation has many consequences. This influences the rheological properties and composition of the sludge.

Defrance *et al.* (2000) observed in a sidestream MBR with high cross-flow velocity that MBR sludge was less viscous than conventional sludge. The same was observed by Rosenberger *et al.* (2002). Furthermore, with increasing shear rate, viscosity of the sludge decreases (Rosenberger *et al.*, 2002), although in some cases, the activated sludge behaves as a Newtonian fluid (Xing *et al.*, 2001). Defrance and Jaffrin (1999) found out that filtering-activated sludge from an MBR resulted in fouling that could be totally, physically removed, whereas filtration of CAS led to physically irremovable fouling.

It is quite difficult to generalize information about sludge composition from different installations, since each installation promotes different types of activated sludge. This has its effect on the microbial community that can be found in an activated sludge system. Nevertheless, it is obvious that the presence of the membrane in an MBR system influences the biomass composition. Since no suspended solids are washed out with the effluent, the only sink is surplus sludge. From a secondary clarifier, lighter species are washed out, whereas in an MBR they are retained in the system by the membrane. Furthermore, changes in SRT and higher MLSS concentrations might lead to changes in the microbial community. Microbial-community analyses have revealed significant differences between CAS system and an MBR and a higher fraction of bacteria was found in the nongrowing state in the MBR (Witzig *et al.*, 2002; Wagner and Rosenwinkel, 2000).

4.16.3.2.3 Sludge production and treatment

Small-scale laboratory studies revealed a great advantage of MBRs, that is, lower or even zero excess sludge production, caused by low loading rates and high SRTs (Benitez *et al.*, 1995). When longer SRTs are applied, sludge production, of course, decreases in the MBR (Wagner and Rosenwinkel, 2000). However, the amount of excess secondary sludge produced in larger MBR installations operated under the practical range of SRTs is somewhat lower than or even equal to that in conventional systems (Günder and Krauth, 2000). **Table 1** provides a general comparison of the sludge-production rates from different treatment processes. It should be noted that the primary sludge production in the case of the MBR is lower. The suited pretreatment for the MBR is grids and/or sieves, and in an average, screened water was observed to contain 30% more solids than settled water (Jimenez *et al.*, 2010). MBR sludge treatment is almost the same compared to CAS systems. The dewaterability of waste-activated sludge from the MBR seems to pose no additional problem, compared to aerobic stabilized waste sludge from CAS systems (Kraume and Bracklow, 2003).

4.16.3.2.4 Space requirements

One of the advantages of the MBR is its compactness, because large sedimentation tanks are not needed. An interesting parameter in this respect is the surface-overflow rates for the two systems. The overflow rate of a secondary clarifier is defined as the ratio of its flow and footprint, that is, the volume of water that can be treated per square meter of tank. In practice, values around $22\,m\,d^{-1}$ are used. For an MBR filtration tank, an overflow rate can also be estimated from the permeate flux and the membrane-packing density within the

Table 1 Sludge production in case of different treatment processes

Treatment process	*Sludge production kg (kg BOD)$^{-1}$*
Submerged MBR	0.0–0.3
Structured media biological aerated filter	0.15–0.25
Trickling filter	0.3–0.5
Conventional activated sludge	0.6
Granular media BAF	0.63–1.06

Data from Stephenson T, Judd S, Jeferson B, and Brindle K (2000) *Membrane Bioreactors for Wastewater Treatment*. London: IWA. Gander MA, Jefferson B, and Judd SJ (2000) Membrane bioreactors for use in small wastewater treatment plants: Membrane materials and effluent quality. *Water Science and Technology* 41: 205–211, and Metcalf and Eddy, Inc. (2003) *Wastewater Engineering – Treatment and Reuse*, 4th edn. New York: McGraw-Hill.

tank. Following this method, Evenblij *et al.* (2005a) showed that with an average permeate flux of $15\,l\,m^{-2}\,h^{-1}$, the overflow rates of the membrane tanks are in the range $25–62\,m\,d^{-1}$ which is up to 3 times higher than the overflow rate of a conventional secondary clarifier. Compared to an average overflow rate of $22\,m\,d^{-1}$ with a secondary clarifier, the space consumption for sludge-water separation in an MBR is 10–60% lower when flux is $15\,l\,m^{-2}\,h^{-1}$ and 50–80% lower when flux is $25\,l\,m^{-2}\,h^{-1}$. A further reduction in footprint is caused by the higher MLSS concentration that can be applied in an MBR. This estimate however did not take into account backflushing or relaxation periods, which reduce the overflow rate. Nevertheless, full-scale MBR plants also manifest these space-saving characteristics. For instance, Brescia WWTP, in Italy, which is the world's largest MBR retrofit of an existing conventional plant, gives a full-scale example of a ratio of 2 when comparing area needed by CAS and MBR (Brepols *et al.*, 2008).

4.16.3.2.5 Wastewater treatment cost

The high cost connected with MBR is often mentioned in discussions about applicability of MBR. However, it is not easy to make a general economical comparison between MBR and CAS systems. First of all, the reference system should not simply be an activated sludge system, but a system that produces an effluent of the same quality. Moreover, an MBR is a modular system, that is, easily expandable, which is often mentioned as an advantage of the system. However, this makes the system less competitive with conventional systems, since these become relatively less expensive per population equivalent (p.e.) at larger scale. It should be noted that although the equipment and energy costs of an MBR are higher than systems used in conventional treatment, total water costs can be competitive due to the lower footprint and installation costs (Pearce, 2008b; Lesjean *et al.*, 2004; Cote *et al.*, 2004; De Wilde *et al.*, 2003). MBR costs have declined sharply since the early 1990s, falling typically by a factor of 10 in 15 years. As MBR technology has become accepted, and the scale of installations has increased, there has been a steady downward trend in membrane prices (Figure 6), which is still continuing. This is particularly notable with the acceptance of the MBRs in the municipal sector. The uptake of membrane technology for municipal applications has had the affect of downward pressure on price. A detailed holistic cost comparison may reveal reasonably comparable results between the cost of the MBR option versus other advanced treatment options, especially if land value is considered.

Studies show that depending on the design and site-specific factors the total water cost associated with MBR may be less or higher than the CAS-UF/MF option. For example, a cost comparison by the US consultant HDR in 2007 showed that MBR was 15% more expensive on a 15 million liters a day (MLD) case study, whereas a study by Zenon in 2003 gave MBR 5% lower costs (Pearce, 2008a). The differences were due to the design fluxes assumed and the capital charge rate for the project. Neither study allocated a cost advantage from the reduced footprint, which could typically translate to a treated water cost saving of up to 5%.

It is interesting to evaluate the development in cost estimates over the past several years.

Davies *et al.* (1998) made a cost comparison for two wastewater treatment plants (WWTPs), with capacities of 2350 and 37 500 p.e. With the assumptions they made (e.g., a membrane lifetime of 7 years) they conclude that depending on the design capacity (i.e., 2 times DWF to be treated) MBR is competitive with conventional treatment up to a treatment capacity of $12\,000\,m^3\,d^{-1}$ (Table 2).

Engelhardt *et al.* (1998) after carrying out pilot experiments also made a cost calculation for an MBR with a capacity of 3000 p.e., designed for nitrification/denitrification and treatment of 2*DWF. Investment costs were estimated at €3 104 000 (including pretreatment) and operational cost at €194 000 yr^{-1}.

Adham *et al.* (2001) made a cost comparison between MBR oxidation ditch followed by membrane filtration and CAS followed by membrane filtration. They concluded that MBR is competitive with the other treatment systems (Table 3).

Chang *et al.* (2001) report experiments with low-cost membranes. The effect of membrane cost on the investment cost is considerable, but operational problems hinder further application of low-cost membranes. A drawback of the applied membranes is its limited disinfecting capacity.

Van Der Roest *et al.* (2002a) described a cost comparison between an MBR installation and a CAS system with tertiary sand filtration. The calculations were carried out for two new WWTPs with the aim of producing effluent with low

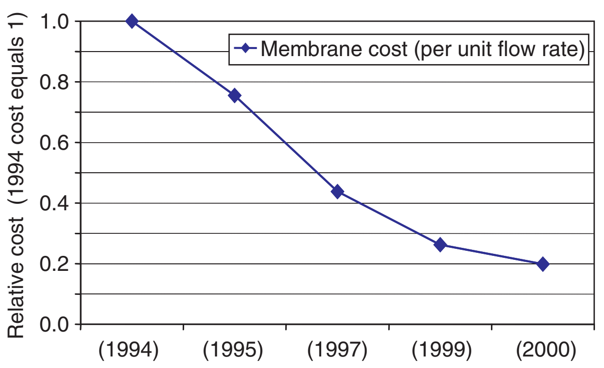


Figure 6 Sharp cost decline of membranes for MBR (cost of Zenon membranes as an example).

Table 2 Capital and operating cost ratios of MBR and conventional activated sludge (CAS) process assuming a capacity of 2*(dry weather flow)

Parameter	*Cost ratio (MBR:ASP)*
Capital cost	
2350 p.e	0.63
37 500 p.e	2.00
Operating costs per year	
2350 p.e	1.34
37 500 p.e	2.27

Data from Davies WJ, Le MS, and Heath CR (1998) Intensified activated sludge process with submerged membrane microfiltration. *Water Science and Technology* 38(5): 421–428.

concentrations of nitrogen and phosphorus. Almost the same investment costs and 10–20% higher operating costs, depending on the capacity of the plant, for MBR were estimated (Table 4). Cost differences between an MBR and a traditional WWTP concerning manpower, chemical consumption, and sludge treatment were noted to be minimal.

WERF (2001) summarized operating and water-quality data obtained over 1 year from two MBR pilot plants located at the Aqua 2000 Research Center at the City of San Diego (California) North City Plant. Preliminary cost estimates of the MBR technology were also developed. MBRs demonstrated that their effluent was suitable to be fed directly into an RO process from a particulate standpoint with silt density index (SDI) values averaging well below 3. The MBR effluent water quality was superior to the quality of a full-scale tertiary conventional WWTP. The preliminary cost estimate in this report was performed for a 1 million gallons a day (mgd) scalping facility (WWTP drawing a designated amount of flow from the sewer system; excess sewage flow is treated at another plant located at the end of the sewer line). This facility produced an effluent suitable as feedwater for an RO process. Based upon this estimate, the present value was estimated as \$0.81 m^{-3}, \$0.96 m^{-3}, and \$1.16 m^{-3} for the MBR process, oxidation ditch with MF, and oxidation ditch with conventional tertiary lime pre-treatment, respectively. Therefore, the MBR process was reported as the most cost-effective alternative for water reclamation where demineralization or indirect drinking water-production (RO) is required.

McInnis (2005) reported a detailed comparative cost analysis of two membrane-based tertiary treatment options: (1) MBR and, (2) CAS process followed by MF (CAS/MF). According to that study, irrespective of design flow rate, the MBR entails slightly higher unit capital costs as compared to CAS/MF process, while, depending on the design flow rate, the operation and maintenance costs (O&M) of the former are higher than or comparable to that of the latter. Comparative O&M cost breakdown revealed that MBR entails less labor cost, considerably higher power and chemical consumptions and slightly higher membrane cost, other costs remaining virtually the same. In the CAS/MF process, labor cost induces the highest cost, while in case of the MBR process, labor and electrical power-consumption costs are almost similar. Overall, the MBR imposes slightly higher capital and operating/maintenance cost over that of CAS/MF.

Cote *et al.* (2004) explored two membrane-based options available to treat sewage for water reuse, tertiary filtration (TF) of the effluent from a CAS process, and an integrated MBR. These options were compared from the point of view of technical performance and cost using ZeeWeed immersed membranes. The analysis showed that an integrated MBR is less expensive than the CAS-TF option. The total life cycle costs for the treatment of sewage to a quality suitable for irrigation reuse or for feeding RO decreased from 0.40\$ m^{-3} to 0.20\$ m^{-3} as plant size increased to 75 000 $m^3\,d^{-1}$. It was also shown that the incremental life-cycle cost to treat sewage to indirect potable water-reuse standards (i.e., by UF and RO) was only 39% of the cost of seawater desalination.

A recent market research report (BCC Research, 2008) estimated the capital cost of a 50 000 gallons per day (gpd) (190 $m^3\,d^{-1}$) plant at US\$350 000, a 100 000 gpd plant at US\$500 000, and a 500 000 gpd plant at US\$2 million. For systems of 1 mgd (million gallons per day) and larger, capital costs start at US\$3.5 million (Table 5). The largest percentage of new system installations, 93%, continue to fall into the 5000–500 000 gpd range (most of those, about 57% of them, have capacities of less than 25 000 gpd), 2% of installations range from 0.5–1 mgd, and 5% of them are larger than 1 mgd.

Tables 2–5 list cost values reported during the period 1998–2008. Obviously, the data from the initial stage of the MBR development holds little relevance today. However, these are listed here to provide a general trend of cost-data evolution.

Table 3 Capital and total cost ratios of MBR and tertiary MF following alternative biological processes

Alternatives	*Cost ratio (MBR:alternative)*	
	Capital	*Total per year*
Oxidation ditch-MF	0.91	0.89
CAS-MF	0.85	0.9

Data from Adham S, Mirlo R, and Gagliardo P (2000) Membrane bioreactors for water reclamation – phase II. *Desalination Research and Development Program Report No. 60*, *Project No. 98-FC-81-0031.* Denver, CO: US Department of the Interior, Bureau of Reclamation, Denver Office.

Table 4 Capital and total cost ratios of MBR and tertiary sand filtration following CAS

Parameter	*Cost ratio*
Capital cost	
10 000 p.e	0.92
50 000 p.e	1.01
Operating costs per year	
10 000 p.e	1.09
50 000 p.e	1.21

Data from Van Der Roest HF, Lawrence DP, and Van Bentem AG (2002a) *Membrane Bioreactors for Municipal Wastewater Treatment (Water and Wastewater Practitioner Series: Stowa Report).* London: IWA.

4.16.3.2.6 Comparative energy usage

MBR provides an equivalent treatment level to CAS-UF/MF, but at the expense of higher energy cost since the efficiency of air usage in MBR is relatively low. The MBR process uses more

Table 5 Capital cost of MBR depending on plant size[a]

Plant size, gpd $\times 10^3$	*Capital cost, US\$* $\times 10^3$
50	350
100	500
500	2000
1000	3500

[a] 1 $m^3\,d^{-1}$ = 264.17 gpd.

Data from BCC Research (2008) Membrane bioreactors: Global markets. *Report Code MST047B, Report Category – Membranes & Separation Technology.*

air, and hence higher energy than conventional treatment. This is because aeration is required for both the biological process and the membrane cleaning, and the type, volume, and location of air required for the two processes are not matched. Biotreatment utilizes fine air bubbles, since oxygen needs to be absorbed for the biological reaction step. In contrast, fouling control is best achieved by larger bubbles, since the air is required to scour the membrane surface or shake the membrane to remove the foulant. Accordingly, although the concept of MBR was first developed to exploit the fact that the biological wastewater-treatment process and the process of membrane-fouling control can both use aeration (Pearce, 2008b), the potential for dual-purpose aeration is strictly limited.

Based on a survey of conventional wastewater-treatment facilities in the US, Metcalfe and Eddy, Inc. (2003) reported that the energy usage range was 0.32–0.66 $kW\,h^{-1}\,m^{-3}$. Energy usage in wastewater treatment is somewhat lower in Europe, partly due to a greater consciousness for energy efficiency, and partly due to the fact that average BOD loading/capita in the US is 20–25% greater than that in Europe (due to the use of kitchen disposal units). Long-term monitoring of wastewater-treatment systems has shown usages as low as 0.15 $kW\,h^{-1}\,m^{-3}$ for activated sludge, increasing to 0.25 $kW\,h^{-1}\,m^{-3}$ if a biological aerated filter (BAF) stage is included (Pearce, 2008a). Membrane filtration after conventional treatment is estimated to add 0.1–0.2 $kW\,h^{-1}\,m^{-3}$ to the energy, equivalent to a total energy use for CAS-UF/MF of 0.35–0.5 $kW\,h^{-1}\,m^{-3}$ in a new facility (Lesjean *et al.*, 2004). Experience in large-scale commercial MBRs shows an energy usage of around 1.0 $kW\,h^{-1}\,m^{-3}$, although smaller-scale facilities typically operate at 1.2–1.5 $kW\,h^{-1}\,m^{-3}$ or higher (Judd, 2006). However, in comparison to these values, energy consumption of around 1.9 $kW\,h^{-1}\,m^{-3}$ was reported in 2003 (Zhang *et al.*, 2003) and up to 2.5 $kW\,h^{-1}\,m^{-3}$ in 1999 (Ueda and Hata, 1999). This proves that there is a gradual improvement in MBR design (**Figure 7**). Further improvements in air efficiency and membrane-packing density are expected to improve the current values in the future. Even so, it seems likely that MBR energy costs will continue to exceed those of CAS-UF/MF by 0.4 $kW\,h^{-1}\,m^{-3}$ or more (Pearce, 2008a). However, the fact that membrane filtration after conventional treatment is estimated to add only 0.1–0.2 $kW\,h^{-1}\,m^{-3}$ to the energy points out that the higher energy consumption of MBR over CAS-UF/MF is due to the difference in consumption in the respective biological processes. MBRs are generally operated at quite low F/M ratios (less than 0.2), or high MLSS concentrations, and this is one of the reasons for the excellent biodegradation efficiency, and high aeration cost as well. CAS plants, on the other hand, are operated at higher F/M ratios, implying lower oxygen need for biodegradation.

Table 6 lists typical energy-use rates of different biological-based treatment combinations.

Section 4.16.5 provides further information on energy comparison of the MBR formats.

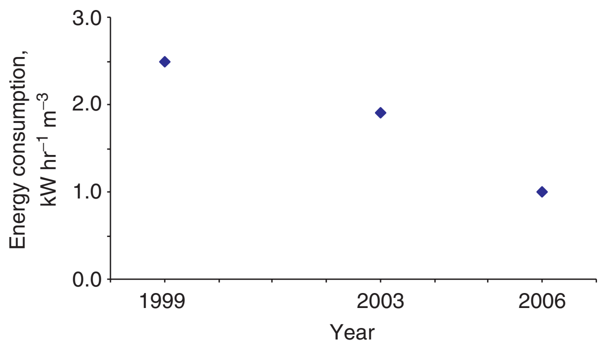


Figure 7 Gradual reduction in reported values of energy consumption by MBR. Data from Ueda T and Hata K (1999) Domestic wastewater treatment by a submerged membrane bioreactor with gravitational filtration. *Water Research* 33: 2888–2892; Zhang SY, Van Houten R, Eikelboom DH, *et al.* (2003) Sewage treatment by a low energy membrane bioreactor. *Bioresource Technology* 90: 185–192; and Judd S (ed.) (2006) *The MBR Book: Principles & Applications of MBRs in Water & Wastewater Treatment*. Oxford: Elsevier.

4.16.3.3 Relative Advantages of MBR

There are several advantages associated with the MBR technology, which make it a valuable alternative over other treatment techniques. The combination of activated sludge with membrane separation in the MBR results in efficiencies of footprint, effluent quality, and residual production that cannot be attained when these same processes are operated in sequence. The MBR system is particularly attractive when applied in situations where long biological solid-retention times are necessary and physical retention and subsequent hydrolysis are critical to achieving biological degradation of pollutants (Chen *et al.*, 2003). The prime advantages of MBR are the treated water quality, the small footprint of the plant, less sludge production, and flexibility of operation (Visvanathan *et al.*, 2000).

First of all, the retention of all suspended matter and most of the soluble compounds within the bioreactor leads to excellent effluent quality capable of meeting stringent discharge requirements and paving the way for direct water reuse. The possibility of retaining all bacteria and viruses results in a sterile effluent, eliminating extensive disinfection and the corresponding hazards related to disinfection by-products. As the entire process equipment can be made airtight, odor dispersion can be prevented quite successfully. Since suspended solids are not lost in the clarification step, total separation and control of the SRT and hydraulic retention time (HRT) are possible enabling optimum control of the microbial population and flexibility in operation.

The absence of a clarifier, which also acts as a natural selector for settling organisms, enables sensitive, slow-growing

Table 6 Comparative typical energy consumption by different treatment options

Treatment option	*Energy use ($kW\,h^{-1}\,m^{-3}$)*
CAS	0.15
CAS-BAF	0.25
CAS-MF/UF	0.35–0.5
MBR	0.75–1.5[a]

[a]Power consumption range for large- to smaller-scale plants.

species (nitrifying bacteria, bacteria capable of degrading complex compounds) to develop and persist in the system (Cicek *et al.*, 2001; Rosenberger *et al.*, 2002). The membrane not only retains the entire biomass but also prevents the escape of exocellular enzymes and soluble oxidants creating a more active biological mixture capable of degrading a wider range of carbon sources (Cicek *et al.*, 1999b).

MBRs eliminate process difficulties and problems associated with settling, which is usually the most troublesome part of wastewater treatment. The potential for operating the MBR at very high SRTs without the obstacle of settling allows high biomass concentrations in the bioreactor. Consequently, higher-strength wastewater can be treated and lower biomass yields are realized (Muller *et al.*, 1995). This also results in more compact systems than conventional processes, significantly reducing plant footprint and making it useful in water-recycling applications (Konopka *et al.*, 1996). The low sludge load in terms of BOD forces the bacteria to mineralize poorly degradable organic compounds. The higher biomass loading also increases shock tolerance, which is particularly important where feed is highly variable (Xing *et al.*, 2000). The increased endogenous (autolytic) metabolism of the biomass (Liu and Tay, 2001) under long SRT allows development of predatory and grazing communities, with the accompanying trophic-level energy losses (Ghyoot and Verstraete, 1999). These factors, in addition to resulting in lower overall sludge production, lead to higher mineralization efficiency than those of a CAS process. High molecular weight soluble compounds, which are not readily biodegradable in conventional systems, are retained in the MBR (Cicek *et al.*, 2002). Thus, their residence time is prolonged and the possibility of oxidation is improved. The system is also able to handle fluctuations in nutrient concentrations due to extensive biological acclimation and retention of decaying biomass (Cicek *et al.*, 1999a).

4.16.3.4 Factors Influencing Performance/Design Considerations

This section sheds light on some important design considerations of MBR. More detailed information on some of these parameters is provided in Section 4.16.4.7, in relation to membrane fouling.

4.16.3.4.1 Pretreatment

All MBRs require pretreatment, for example, screening and grit removal, to protect the membranes. Screening has historically been limited to 3 mm; however, hair and fiber can still pass through this size of the screen and become embedded or wrapped around the hollow fibers. The MBR providers have standardized their screen selections to a 2-mm traveling band, punched screen. Conversely, the flat-sheet membranes experience less problems with hair and fiber, and are standardized to a 3-mm screen. Further discussion regarding mechanical pretreatment is provided in Section 4.16.4.6.

4.16.3.4.2 Membrane selection and applied flux

An MBR membrane needs to be mechanically robust, chemically resistant to high Cl_2 concentrations used in cleaning, and nonbiodegradable (Pearce, 2008a). Clean-water permeability is not as important in an MBR as in membrane-filtration applications, since the membrane transport properties are strongly influenced by the accumulation of foulant particles at the membrane surface. However, process flux in treating a wastewater feed is important since it directly affects capital cost, due to its effect on membrane area and footprint, and operating costs due to the effect of membrane area on chemical and air use. Most MBRs operate at an average flux rate between 12.5 and 25 $l\,m^{-2}\,h^{-1}$, with Mitsubishi's unit operating in the lower range. The key flux rates that determine the number of membranes required are associated with the peak flow rates. For plants with peaking factors of less than two, an MBR can handle the plant flow variation without having a significantly impact on the average design flux rate. Otherwise, equalization needs to be provided with either a separate tank at the head of the facility or within the aeration basin, allowing sidewater depth variations during peak flow.

4.16.3.4.3 Sludge retention time

In the past, most MBR systems were designed with extremely long SRTs, of the order of 30–70 days, and very few were operated at less than about 20 days. Two reasons prompted such practice: (1) the drive to minimize sludge production or eliminate it all together and (2) the concern over the reduced flux resulting from short SRT operation, presumably due to the fouling effect of extracellular excretions from younger sludge. Currently, the selection of SRT is based more on the treatment requirements, and SRTs as low as 8–10 days can now be contemplated.

4.16.3.4.4 Mixed liquor suspended solids concentration

From the point of view of bioreactor volume reduction and minimization of excess sludge, submerged MBR systems have been typically operated with MLSS concentrations of more than 12 000 $mg\,l^{-1}$, and often in the range of 20 000 $mg\,l^{-1}$. Hence, they offer greater flexibility in the selection of the design SRT. However, excessively high MLSS may render the aeration system ineffective and reduce membrane flux. A trade-off, therefore, comes into play. Current design practice is to assume the MLSS to be closer to 10 000 $mg\,l^{-1}$ to ensure adequate oxygen transfer and to allow for higher membrane flux. With larger systems, it is more cost effective to reduce the design MLSS because of the high relative cost of membranes when compared to the cost of additional tank volume.

4.16.3.4.5 Oxygen transfer

At high MLSS concentrations, the demand for oxygen can be significant. In some cases, the demand can exceed the volumetric capacity of typical oxygenation systems. The oxygen-transfer capacity of the aeration system must also be carefully analyzed. Submerged membranes are typically provided with shallow coarse bubble air to agitate the membranes as a means to control fouling. Such aeration provides some oxygenation, but at low efficiency. In compact systems, fine bubble aeration may be placed at greater depth below the membrane aeration; however, the combined efficiency and the bubble-coalescing effects require further consideration during design (Visvanathan *et al.*, 2000).

The lower operating cost obtained with the submerged configuration along with the steady decrease in the membrane cost encouraged an exponential increase in MBR plant installations from the mid-1990s onward. Since then, further improvements in the MBR design and operation have been introduced and incorporated into larger plants. The key steps in the recent MBR development are summarized below:

- The acceptance of modest fluxes (25% or less of those in the first generation), and the idea of using two-phase bubbly flow to control fouling.
- While early MBRs were operated at SRTs as high as 100 days with MLSS up to $30\,g\,l^{-1}$, the recent trend is to apply a lower SRT (around 10–20 days), resulting in more manageable MLSS levels ($10–15\,g\,l^{-1}$).
- Thanks to these new operating conditions, the fouling propensity in the MBR has tended to decrease and overall maintenance has been simplified, as less-frequent membrane cleaning is necessary.

Further discussion on these aspects is provided in the following sections.

4.16.4 Worldwide Research and Development Challenges

4.16.4.1 Importance of Water Reuse and the Role of MBR

The need for pure water is a problem of global proportions. In the Earth's hydrologic cycle, freshwater supplies are fixed and constant, while global water demand is growing (Howell, 2004; Bixio *et al.*, 2006). With each passing year, the quality of the planet's water measurably deteriorates, presenting challenges for the major users: the municipal, industrial, and environmental sectors. Increasing demand for water, and drought and water scarcity are now common issues facing many urban and rural communities around the world (Howell, 2004; Tadkaew *et al.*, 2007; Jimenez and Asano, 2008). Water treatment has, therfore, become an area of global concern as individuals, communities, industries, countries, and their national institutions strive for ways to keep this essential resource available and suitable for use. Water recycling is a pragmatic and sustainable approach for many countries to mitigate or solve the problems of water supply. There is a growing interest in using nontraditional water resources by means of water reclamation and water recycling for long-term sustainability. It can be divided into two categories, internal domestic or industrial recycling and external recycling, where high-quality reclaimed water from a sewage treatment plant is used for aquifer recharge or irrigation.

With the current focus on water-reuse projects and the role they play in the water cycle, the search for cost-competitive advanced wastewater-treatment technologies has never before been so important. Treatment technology for water recycling encompasses a vast number of options. A general paucity of legislative and socioeconomic information has led to the development of a diverse range of technical solutions (Jefferson *et al.*, 2000). Membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are included in a number of prominent schemes worldwide, for example, for artificial groundwater recharge, indirect potable reuse, as well as for industrial-process water production (Melin *et al.*, 2006; Bixio *et al.*, 2008). Among the many treatment alternatives, MBRs, which combine membrane filtration and biological process for wastewater treatment, are seen to have an effective technology capable of transforming various types of wastewater into high-quality effluent exceeding most discharge requirements and suitable for a variety of nonpotable water-reuse applications such as flushing toilets and for irrigation (Tadkaew *et al.*, 2007; Jimenez and Asano, 2008). In some cases, treated water can be applied to recharge groundwater to halt saltwater intrusion into coastal aquifers, abate subsidence in areas sinking due to overpumping groundwater, and support aquifer storage and recovery.

Issues of water quality, water quantity, and aging/nonexistent infrastructure propel the market for MBRs. Escalating water costs due to dwindling supplies for communities and businesses also drive the growing acceptance of MBRs. Anticipated stricter environmental regulations are driving sales of MBRs to industry, municipalities, and are prompting maritime users to consider MBR technology (Jefferson *et al.*, 2000; Jimenez and Asano, 2008). This is probably due to the effectively disinfected high-quality effluent and high performance in trace organic removal for safe and environmentally benign discharge that MBRs can offer. In practical terms, the process has many benefits, which make it suitable for the size of the systems applicable to recycling. The ability to run independently of load variation and produce no sludge are critical and highlight MBRs as possibly the most viable small-footprint, high-treatment option for water recycling (Jefferson *et al.*, 2000; Melin *et al.*, 2006; Tadkaew *et al.*, 2007).

Comparison with other technologies used for water recycling reveals that MBRs not only produce lower residual concentrations but do so more robustly than the alternatives (Jefferson *et al.*, 2000; Melin *et al.*, 2006). The favorable microbiological quality of the effluent of MBRs is a major factor in their frequent selection for water reuse, even if full disinfection cannot be expected, particularly considering the distribution and storage components of a full-scale system, which can be prone to regrowth of microorganism and contamination from various sources. However, the MBR effluent is adequate for many water-reuse applications with little residual chlorine disinfection for subsequent distribution. The MBR then does provide a dual layer of protection against pathogen breakthrough, greatly lowering the risk during operation.

MBRS have the greatest efficacy toward water recycling, albeit contingent upon a loading rate constrained by the operable flux. Not only do they comply with all likely water-quality criteria for domestic recycling but they also produce a product that is visibly clear and pathogen free, both of which are likely to be key concerns in terms of public acceptability. There are some issues that still need to be addressed and these are highlighted throughout Sections 96.4.6 and 96.4.7 of this chapter.

4.16.4.2 Worldwide Research Trend

Early development efforts in MBR technology were concentrated in UK, France, Japan, and South Korea, whereas extensive research in China and Germany began after 2000. Much

of the research in the newcomer countries is building on pioneering work from the UK, France, Japan, and South Korea.

Three stages may be identified in the worldwide MBR research:

1. An entry-level stage spanning from 1966 to 1980, during which lab-scale research was mainly conducted. Membranes of that period had low flux and short life span due to undeveloped membrane-manufacturing technology.
2. A slow-to-moderate growth period from 1980 to 1995, when MBR technology was well investigated especially in Japan, Canada, and the USA. During this stage, new membrane-material development, MBR configuration design, and MBR operation were critically studied. The submerged MBR concept was put forward by Japanese researchers in 1989.
3. The rapid development stage started in 1995 and continues even now, when MBR technology underwent a rapid development prompted by deep understanding of the technology in research communities and by the installation of full-scale MBRs.

Much of the published information on MBRs to date has mainly focused on bench or pilot-scale studies, performance results of treating a specific type of wastewater, and short-term operations. Regardless of the source of wastewater, whether it is municipal or industrial, very few publications involved full-scale studies for long-term operational periods. In a comprehensive review, Yang *et al.* (2006) grouped the available worldwide publications regarding MBR into six main research areas: (1) literature and critical reviews; (2) fundamental aspect; (3) municipal and domestic wastewater treatment; (4) industrial wastewater and landfill leachate treatment; (5) drinking-water treatment; and (6) others, which include gas removal, sludge treatment, hydrogen production, and gas diffusion. The fundamental research category was based on studies that exclusively looked at membrane fouling, operation and design parameters, sludge properties, microbiological characteristics, cost, and modeling. Studies, which focused on applied research and general reactor performance, were categorized by influent (feed) type (groups 3–6). Membrane fouling, which has been widely considered as one of the major limitations to faster commercialization of MBRs, has been investigated from various perspectives including the causes, characteristics, mechanisms of fouling, and methods to prevent or reduce membrane fouling. More than one-third of studies in the fundamental aspects group were found to deal with issues related to membrane fouling.

4.16.4.3 Modeling Studies on MBR

Models that can accurately describe the MBR process are important for the design, prediction, and control of MBR systems. Due to the intrinsic complexity and uncertainty of MBR processes, basic models that can provide a holistic understanding of the technology at a fundamental level are of great necessity. Complex models that are also practical for real applications can greatly assist in capitalizing on the benefits of MBR technology. However, compared to experimental R&D, followed by commercialization of the technology, modeling studies for system-design analysis and performance prediction are at a relatively preliminary stage. In an attempt to identify the required research initiatives in this regard, this section looks briefly into the state-of-the-art MBR modeling efforts.

Effluent quality and the investment and operating costs are the primary concerns for any given wastewater treatment system. Therefore, model development should center on components for which water-quality standards have been set and parameters which are strongly correlated to cost. Ng and Kim (2007) put forward a few key model components and parameters for MBR modeling:

- The ability to quantify individual resistance (i.e., resistance from cake formation, biofilm formation, and adsorptive fouling) as a function of the various influencing parameters is important in determining which parameters have the greatest influence on fouling and for designing and optimizing the system to achieve an economical balance between production and applied pressure.
- Determining the relationship between biomass concentration and other parameters can aid in identifying an optimal biomass concentration for operation, which can lead to significant economical savings.
- Aeration accounts for a significant portion of energy costs in the operation of MBR systems. The factors that influence oxygen requirement (wastewater and biomass concentration/growth rates) and the oxygen-transfer rate (MLSS concentration, MBR configuration, type of bubbles used, and specific airflow rate) should receive due consideration in the model to optimize aeration.
- Carbon and nutrient (nitrogen and phosphorous components) concentrations and their influencing factors (e.g., respective concentrations and growth rates of the various types of organisms and concentration of oxygen) should be incorporated into the models.
- Soluble microbial products (SMPs), which comprise a major portion of the organic matter in effluents from biological treatment processes and are potentially associated with issues such as disinfection by-product formation, biological growth in distribution systems, and membrane fouling, should be given proper consideration in models.

MBR models available in the literature can be broadly classified into three categories: biomass kinetic models, membrane-fouling models, and integrated models to describe the complete MBR process (Ng and Kim, 2007; Zarragoitia-González *et al.*, 2008).

Models describing biomass kinetics in an MBR include the activated sludge model (ASM) family (Henze *et al.*, 2000), the SMP model (Furumai and Rittmann, 1992; Urbain *et al.*, 1998; de Silva *et al.*, 1998), and the ASM–SMP hybrid model (Lu *et al.*, 2001; Jiang *et al.*, 2008). The ASMs were developed to model the activated sludge process. The MBR process is the activated sludge process with the secondary clarification step replaced by membrane filtration; therefore, it is reasonable to use ASMs to characterize the biomass dynamics in an MBR system. However, their ability to describe the MBR process accurately has not been verified by in-depth experiments.

Research suggests that SMPs are important components in describing biomass kinetics due to high SRTs in MBR systems. Accordingly, the SMP model demonstrated the capability of

characterizing the biomass with a reasonable-to-high degree of accuracy. Lu *et al.* proposed that the modified versions of ASM1 (Lu *et al.*, 2001) and ASM3 (Lu *et al.*, 2002), which incorporate SMPs, demonstrated fairly reasonable accuracy in quantifying COD and soluble nitrogen concentrations. Jiang *et al.* (2008) extended the existing ASM No. 2d (ASM2d) to ASM2dSMP with introduction of only four additional SMP-related parameters. In addition to minimizing model complexity and parameter correlations, the model parameter estimation resulted in reasonable confidence intervals.

Models describing membrane fouling include the empirical hydrodynamic model (Liu *et al.*, 2003), fractal permeation model (Meng *et al.*, 2005), sectional resistance model (Li and Wang, 2006), subcritical fouling behavior model (Saroj *et al.*, 2008), and the resistance-in-series models that were presented as a part of the integrated models. Some of them are simply based on solid–liquid separation and simulate filtration processes (Chaize and Huyard, 1991; Gori *et al.*, 2004). Other models consider specific physical approaches: cross-flow filtration (Cheryan, 1998; Hong *et al.*, 2002; Beltfort *et al.*, 1994) and mass-transport models (Beltfort *et al.*, 1994; Bacchin *et al.*, 2002). Nevertheless, membrane fouling is generally evaluated by employing the resistance-in-series model (Wintgens *et al.*, 2003; Wisniewski and Grasmick, 1998) or, rarely, using empirical models (Benitez *et al.*, 1995; De Wilde *et al.*, 2003).

The integrated models, basically, couple the kinetic models with the fouling ones (such as the resistance-in-series model) and they often consider the formation and degradation of SMPs (Ng and Kim, 2007). The models reported to date are valuable preliminary attempts, but require further improvements. For instance, the empirical hydrodynamic model is too simple to describe the membrane-fouling phenomenon, and the sectional resistance model lacks accuracy. Both the fractal permeation model and resistance-in-series model by Lee *et al.* (2002) provide good scientific insight, but specific experimental verification is necessary for general use of the models. The resistance-in-series model developed by Wintgens *et al.* (2003) shows the most promise, as it is fairly accurate, accounts for cleaning cycles, and can predict permeability changes over time. Further tests are needed to determine whether the model requires calibration or if the model parameters are applicable to other MBR systems.

Recently, Zarragoitia-González *et al.* (2008) included the biological kinetics and the dynamic effect of the sludge attachment and detachment from the membrane, in relation to the filtration and a strong intermittent aeration in a hybrid model. The model was established considering SMP formation–degradation kinetic based on previous published models (Cho *et al.*, 2003; Lu *et al.*, 2001). A modification of Li and Wang's model (Li and Wang, 2006) allows to calculate the increase of the transmembrane pressure (TMP), evaluating, at the same time, the influence of an intermittent aeration of bubbles synchronized with the filtration cycles on fouling control, and to analyze the effects of shear intensity on sludge cake removal. On the other hand, in order to describe the biological system behavior, a modified ASM1 model was used. The final hybrid model was developed to calculate the evolution of sludge properties, its relation to sludge cake growth, and the influence of sludge properties on membrane fouling.

A simple model for evaluating energy demand arising from aeration of an MBR was presented by Verrecht *et al.* (2008) based on a combination of empirical data for membrane aeration and biokinetic modeling for biological aeration. The model assumes that aeration of the membrane provides a portion of the dissolved oxygen needed for biotreatment. The model also assumes, based on literature information sources, a linear relationship between membrane permeability and membrane aeration up to a threshold value, beyond which permeability is unchanged with membrane aeration. An analysis reveals that significant reductions in energy demand are attained through operating at lower MLSS levels and membrane fluxes.

The complete organic removal in MBR is due to all the in-series phenomena: biological degradation of biomass, biological filtration of cake layer, and final filtration of physical membrane. Di Bella *et al.* (2008) set up a mathematical model for the simulation of physical–biological wastewater organic removal for SMBR system. The model consists of two submodels: the first one for the simulation of the biological processes and a second one for the physical processes. In particular, regarding the biological aspects, it is based on the ASM concept. On the other hand, organic-matter removal due to filtration (the physical process) was described by simple models proposed in the literature (Kuberkar and Davis, 2000; Jang *et al.*, 2006; Li and Wang, 2006).

It is conceivable that several of the existing models, particularly the ASMs, require validation to determine their applicability for modeling the MBR process and to evaluate whether they can serve as a base for future MBR model development. Membrane fouling in MBRs is affected by the biotransformation processes in the system; therefore, a more effective integration of biomass kinetics and membrane fouling into the models is required. Moreover, examination of alternative empirical modeling approaches, such as the application of artificial neural networks, is worthwhile to establish a thorough link between inputs and outputs of MBR systems and to find phenomenological interrelationships among components and parameters (Ng and Kim, 2007).

4.16.4.4 Innovative Modifications to MBR Design

Researchers have put forth different modifications to the conventional design of MBRs in order to enhance removal performance and/or mitigate membrane fouling. This section highlights some of such examples (Table 7). The commercialized MBR formats are discussed separately in Section 4.16.5.2.

4.16.4.4.1 Inclined plate MBR

Theoretically, an infinite SRT provides a possibility of naturally achieving zero-excess sludge discharge from MBR under normal environment. It should, however, be noted that zero-excess sludge production is just a theoretical concept which can only be obtained with a feed containing only solutes. In real life, sewage or industrial effluents contain non-biodegradable suspended solids and colloids that accumulate in the reactor, continuously increasing the sludge concentration. Therefore, an immediate challenge encountered at infinite SRT is the extremely high sludge concentration

Table 7 Examples of innovative modifications to MBR design

Modified design	*Main purpose*	*Selected reference*
Inclined plate MBR	Omit excess sludge production and thereby realize long-term stable membrane filtration	Xing *et al.* (2006)
Integrated anoxic–aerobic MBR	Derive the simultaneous advantages of efficient nutrient removal and mitigate membrane fouling (Chae *et al*., 2006 a,b;).	Chae *et al.* (2006a,b), Hai *et al.* (2006b, 2008a)
Jet-loop-type MBR	Treatment of high-strength wastewater without encountering severe fouling	Park *et al.* (2005), Yeon *et al.* (2005)
Biofilm MBR	Enhanced removal of recalcitrant compound and/or membrane fouling mitigation	Lee *et al.* (2006), Leiknes and Odegaard (2007), Ngo *et al.* (2008), Hai *et al.* (2008)
Nanofiltration MBR	Obtain in one step indirect potable reuse standard effluent	Choi *et al.* (2002)
Forward osmosis MBR	Indirect potable reuse along with energy demand reduction	Achilli *et al.* (2009), Cornelissen *et al.* (2008)
Membrane distillation bioreactor (MDBR)	Obtain in one step indirect potable reuse standard effluent	Phattaranawik *et al.* (2008, 2009)

produced in the bioreactor (Wen *et al.*, 1999). Consequently, the method to achieve zero-excess sludge discharge translates into how to realize long-term stable membrane filtration of high-concentration sludge beyond the guideline value of 10–20 g l^{-1} recommended for submerged MBRs when applied to domestic wastewater treatment. In order to omit excess sludge production, Xing *et al.* (2006) proposed an innovative MBR design comprising an anoxic tank equipped with settling-enhancer inclined plates and a subsequent aerobic tank containing the membrane.

The inclined plates together with intermittent air blowing (to blow off gaseous content generated by denitrification, etc.) proved to be quite effective in confining high MLSS sludge within the anoxic tank leading to an MLSS difference of 0.1–13.1 g l^{-1} between the aerobic and anoxic sludge. Consequently, the capability of MBRs in handling the extremely high MLSS challenge encountered especially at zero-excess sludge could be extended. Results indicated that at an HRT of 6 h, average removals of COD, ammonia nitrogen, and turbidity were 92.1, 93, and 99.9%, resulting in daily averages of 12.6 mg COD l^{-1}, 1.3 mg NH_3–N l^{-1}, and 0.03 NTU, respectively.

4.16.4.4.2 Integrated anoxic–aerobic MBR

In contrast to separate anoxic tanks for denitrification or creation of alternating anoxic/oxic conditions within the same tank by intermittent aeration, an integrated anoxic/oxic MBR, containing anoxic/oxic compartments in one reactor, was developed to derive simultaneous advantages of efficient nutrient removal (Chae *et al.*, 2006a, 2006b) and mitigated membrane fouling (Chae *et al.*, 2006a, 2006b; Hai, 2007; Hai *et al.*, 2007; Hai *et al.*, 2006b; Hai *et al.*, 2008a).

Under the optimal volume ratio of anoxic and oxic zones of 0.6 and the desirable internal recycle rate and HRT of 400% and 8 h, respectively, the average removal efficiencies of total nitrogen (T-N) and total phosphorus (T-P) were 75% and 71%, respectively (Chae *et al.*, 2006b). Furthermore, comparison with sequential anoxic/oxic MBR under the same conditions revealed the membrane-fouling reduction potential of this specific design (Chae *et al.*, 2006a).

Working with a high-strength industrial wastewater, Hai *et al.* (2006a, 2006b, 2008a) demonstrated minimization of excess sludge growth and maintenance of less MLSS concentration in contact with the membrane at the aerobic zone by exploring a similar reactor design along with a strategy of splitting the feed through the two zones.

4.16.4.4.3 Jet-loop-type MBR

The so-called high-performance compact reactor (HCR) which is a jet-loop-type reactor with a draft tube and a two-phase nozzle was coupled with a submerged membrane by Park *et al.* (2005). The HCR is able to deal with very high organic loading rates due to the high efficiency of oxygen transfer, mixing, and turbulence achieved. The significant amount of bubbles and turbulence present in the HCR can be beneficial in retarding fouling of the submerged membrane. The developed MBR showed much greater membrane permeability than the conventional MBR, promising very high potential for the treatment of high-strength wastewater without encountering severe fouling (Park *et al.*, 2005; Yeon *et al.*, 2005).

4.16.4.4.4 Biofilm MBR

Membrane-coupled moving-bed biofilm reactor system, wherein the membrane is submerged within the same tank (Lee *et al.*, 2006) or in an additional tank (Leiknes and Odegaard, 2007), has been extensively studied in association with different kinds of biocarriers. Powdered activated carbon (PAC) which also acts as an adsorbent is commonly added into the bioreactor as the biocarrier (Ng *et al.*, 2006; Hai, 2007; Hai *et al.*, 2008b). However, carriers made of inert materials, such as plastic (Leiknes and Odegaard, 2007) and sponge (Lee *et al.*, 2006; Ngo *et al.*, 2008), have also been used. Biomass granulation with shell-support media coupled with membrane separation is also worth mentioning in this context (Thanh *et al.*, 2008).

The mechanisms of enhanced removal and/or membrane-fouling mitigation depend on the specific design and the utilized biocarrier type. For example, in an integrated membrane-coupled moving-bed biofilm reactor using sponge as the biocarrier, frictional force exerted by the circulating

carrier on the submerged membrane reduced the formation of cake layer on the membrane surface and thus enhanced the membrane permeability (Lee *et al.*, 2006). On the other hand, Leiknes and Odegaard (2007) demonstrated that operation under high volumetric-loading rates of 2–8 kg COD m^{-3} $d^{-1}$and HRTs up to 4 h and maintenance of membrane fluxes around 50 l m^{-2} h^{-1} were possible by placing the moving-bed biofilm reactor prior to the submerged MBR. The specific purpose of the biofilm reactor in this case was to reduce the organic loading on MBR. Ng *et al.* (2006) contend that the improved membrane performance of the MBR with added PAC could be due to a number of factors including, PAC providing sink for some of the fouling components and the scouring action of PAC. Hai *et al.* (2008b) reported that simultaneous PAC adsorption within a fungi-MBR treating dye wastewater resulted in multiple advantages including co-adsorption of dye and fungal enzyme onto activated carbon and subsequent enzymatic dye degradation.

4.16.4.4.5 Nanofiltration MBR

The potential for using NF technology in wastewater treatment and water reuse is noteworthy. A new concept with the addition of RO membrane after conventional MBR has been recently developed to reclaim municipal wastewater. The new MBR-RO process demonstrated the capability of producing the same or more consistent product quality (in terms of total organic carbon (TOC), NH_4, and NO_3) and sustained higher flux compared to the CAS-MF-RO process in reclamation of domestic sewage (Qin *et al.*, 2006).

Choi *et al.* (2002, 2007), on the other hand, demonstrated the technical feasibility of a submerged NF-MBR. For the initial 130 days, the NF-MBR achieved high permeate quality (DOC concentration = 0.5–2.0 mg l^{-1}) and maintained reasonable water productivity. With low electrolyte rejection, operation under a low suction pressure was possible, and electrolyte accumulation in the bioreactor, which may hinder biological activity, did not occur. The permeate quality, however, deteriorated to some extent (DOC concentration = 3.0 mg l^{-1}) due to the deterioration of the cellulose membrane.

4.16.4.4.6 Forward osmosis MBR

The forward osmosis (FO)–MBR is an innovative technique for the reclamation of wastewater, which combines activated sludge treatment and FO membrane separation with an RO posttreatment. FO membranes, either submerged or external, are driven by an osmotic pressure difference over the membrane. Through osmosis, water is transported from the mixed liquor across the semipermeable membrane into a draw solution (DS) with a higher osmotic pressure. To produce potable water, the diluted DS is then treated in an RO unit, and the concentrated DS is reused in the FO process.

The FO-MBR is expected to have the same advantages as conventional MBRs; however, it has to deal with the most important drawback, that is, a high energy demand. In this system, FO membranes with structures comparable with NF or RO membranes are used instead of MF/UF membranes for the separation of suspended solids, multivalent ions, natural organic matter, and biodegradable materials. Since fluxes are generally lower and no internal fouling occurs, fouling of NF or RO membranes, compared to that of the MF or UF membranes in conventional MBR, may be dealt with easily. The RO system after FO-MBR can be operated with higher fluxes because all the bivalent ions are removed in the FO-MBR.

Recent studies have demonstrated high sustainable flux and relatively low reverse transport of solutes from the DS into the mixed liquor, along with very high removal performance (Achilli *et al.*, 2009; Cornelissen *et al.*, 2008).

4.16.4.4.7 Membrane distillation bioreactor

A novel wastewater-treatment process known as the membrane distillation bioreactor (MDBR) incorporating membrane distillation in an SMBR operated at an elevated temperature was developed and experimentally demonstrated by Phattaranawik *et al.* (2008, 2009). The ability of membrane distillation (MD) to transfer only volatiles means that very high quality treated water is obtainable, with TOC levels below 1 ppm and negligible quantity of salts. A unique feature is that the MDBR allows for organic retention times to be much greater than the HRT. The TOC in the permeate was consistently lower than 0.7 mg l^{-1} for all experiments. Stable fluxes in the range 2–5 l m^{-2} h^{-1} have been sustained over extended periods. The MDBR was described to have the potential to achieve in a single step, the reclamation obtained by the combined MBR + RO process. It was also suggested that for viable operation, it would be necessary to use low-grade (waste) heat and water cooling.

Several other emerging approaches are also noticeable in contemporary literature. These include hybrid MBR-CAS concept (De Wilde *et al.*, 2009), anaerobic baffled reactor-MBR combination (Pillay *et al.*, 2008), etc.

4.16.4.5 Technology Benefits: Operators' Perspective

The relative advantages of MBR over the CAS process were outlined in Section 4.16.3.3. This section highlights the technical benefits of MBRs cited by the operators:

1. high-quality effluent, ideal for post membrane treatments (e.g., NF and UF);
2. space savings, enabling upgrading of plants without land expansion;
3. shorter start-up time compared to conventional treatment systems;
4. low operating and maintenance manpower requirement (average of 1.7 working hours per MLD); and
5. (5) automated control.

4.16.4.6 Technology Bottlenecks

MBR technology is facing some research and development challenges. The technology bottlenecks as reported in the literature include (Howell, 2002, 2004; Lesjean *et al.*, 2004; Le-Clech *et al.*, 2005a; Yang *et al.*, 2006; Melin *et al.*, 2006)

1. *Membrane fouling*. Further understanding the mechanisms of membrane fouling and developing more effective and easier methods to control and minimize membrane fouling.
2. *Pretreatment*. Effective methods to limiting membrane clogging and operational failures.

3. *Membrane life span*. Increasing membrane mechanical and chemical stability.
4. *Cost*. Further reduction of costs for maintenance and replacement of membranes, energy requirement, and labor requirements.
5. *Plant capacity*. Scaling up for large plants.
6. *Exchangeability of modules*. Module exchangeability between different brands (reduction of costs for replacement of membranes).

Some other problems often encountered by the operators include (Leslie and Chapman, 2003; Adham *et al.*, 2004; Le-Clech *et al.*, 2005a; Yang *et al.*, 2006)

- membrane fouling during permeate backpulsing,
- entrained air impacting suction-pump operation,
- bioreactor foaming,
- inefficient aeration due to partial clogging of aerator holes,
- no significant decrease of biosolid production,
- scale buildup on membrane and piping,
- corrosion of concrete, hand rails, and metallic components due to corrosive vapor produced during high temperature NaOCl cleaning,
- membrane delamination and breakage during cleanings,
- odor from screening, compaction, drying beds, and storage areas (although normally less than in CAS), and
- failure of control system.

Although the commercialization of MBRs has expanded substantially in the past 20 years, target markets have not been tapped to a large extent and new potential areas of applications are continually developing. The R&D challenges mentioned above, when tackled, will lead to a more competitive and mature market for MBR applications. Lesjean *et al.* (2004) contend that academic research is addressing only some of these issues. For instance, while many publications on fouling are being produced and some cost studies are conducted, no significant research efforts have addressed membrane life span, pretreatment, and scale-up issues. Academic researchers can expect interest from MBR companies and plant operators on these subjects, and should direct some of their research programs to address these needs.

Among the challenges underscored by the experts, membrane fouling is one of the most serious problems that has retarded faster commercialization of MBR technology. The causes, characteristics, mechanisms of fouling, and methods to prevent or reduce membrane fouling are discussed elaborately in Section 4.16.4.7; Section 4.16.5.5 sheds light on the issue of exchangeability of modules. The remainder of the current section will be devoted to the issues closely related to membrane fouling and performance, that is, mechanical pretreatment and membrane integrity:

- *Pretreatment*. Pretreatment is one of the most critical factors for ensuring a stable and continuous MBR operation. Due to membrane sensitivity to the presence of foreign bodies, fine prescreening of the feed (and sometimes of the mixed liquors) must occur. The type of sieve installed is very important with regard to the total screening of hair and fibers. Recent studies (Frechen *et al.*, 2006; Schier *et al.*, 2009) have shown sieves with smaller gap sizes and with two-dimensional gap geometries to perform better. On the other hand, even intensive long-term pilot plant trials can fail to suggest the effective scale-up design of the sieve (Melin *et al.*, 2006). If too many clogging problems occur, the original pre-screen systems are usually upgraded to finer screens. However, when both the influent and the mixed liquor are filtered with a fine prescreen, a large amount of trash is produced (up to 3.8 m^3 per week for a 1.4 MLD plant) (Le-Clech *et al.*, 2005a; Melin *et al.*, 2006; Schier *et al.*, 2009). It should be noted that the investment in pretreatment is of little use if the bioreactor is uncovered, in which case, different sorts of debris can easily enter the bioreactor. It is recommended to remove these items using a high-pressure water hose. However, many MBR users report that this type of manual cleaning causes membrane-fiber breakage. In order to keep the membrane effectively separated from the fibrous materials, Schier *et al.* (2009)proposed the following mechanical-treatment concept: conventional pretreatment including screen and grit chamber/grease trap to be placed before the biological tank, causing braid of hair and fibers formed therein to be removed by the sieve placed before the separate filtration chamber housing the membrane modules.
- *Membrane integrity*. A major problem facing MBR systems is the loss of membrane integrity, which leads to the permeate-quality deterioration and ineffective backwashing. When breakage occurs in a submerged hollow-fiber MBR system, continuous filtration may allow solids and particles to quickly clog the broken fiber. However, application of backwash would force the solids out of the fiber. Accordingly, once damaged, disinfection of the product water would be compromised and it would also cause the loss of the backwash efficiency; and the faulty membrane/module would need to be changed quickly.

Faulty installation is one obvious reason for membrane failure. Once under pressure, an incorrectly installed membrane module can be compressed. Other reasons associated with regular operation include frequent and/or extended contact between membrane and cleaning solution causing delamination of the membrane, scoring and cleaving of the membrane resulting from the presence of abrasive or sharp-edged materials in the influent, and operating stress and strain occurring in the system due to fiber movement and membrane backwashing. A better understanding of the effect of membrane material, age, and fouling on membrane integrity may be gained from hollow-fiber-tensile test reported in the literature (Childress *et al.*, 2005; Gijsbertsen-Abrahamse *et al.*, 2006).

Even flat-sheet membranes used in MBRs are not immune to occasional failure (Cornel and Krause, 2003). The construction of current flat-sheet MBR membrane panels is a labor-intensive, multistep operation. These are typically sandwich constructions with three separate layers. Two of them are pre-fabricated membrane layers, while the third one is a permeate drainage layer which is sandwiched between them. The three layers of the sandwich are held together by gluing or laminating techniques over their entire surface or just at their edges. Flat-sheet membranes have been found to be sensitive to breaking near the top

due to poor adhesion of the membrane to the support layer (Doyen *et al.*, 2010).

4.16.4.7 Membrane Fouling – the Achilles' Heel of MBR Technology

Although MBR has become a reliable alternative to CAS processes and an option of choice for many domestic and industrial applications, membrane fouling and its consequences in terms of plant maintenance and operating costs limit the widespread application of MBRs (Le-Clech *et al.*, 2006). Membrane fouling can be defined as the undesirable deposition and accumulation of microorganisms, colloids, solutes, and cell debris within pores or on membrane surface (Meng *et al.*, 2009). It results from the interaction between the membrane material and the components of the activated sludge liquor, which include biological flocs formed by a large range of living microorganisms along with soluble and colloidal compounds. Thus, it is not surprising that the fouling behavior in MBRs is more complicated than that in most membrane applications. The suspended biomass has no fixed composition and varies with both feedwater composition and MBR operating conditions employed. Accordingly, although many investigations of membrane fouling have been published, the diverse range of operating conditions and feedwater matrices employed, and the limited information reported in most studies on the biomass composition in suspension or on the membrane, have made it difficult to establish any generic behavior pertaining to membrane fouling in MBRs.

Three fouling phenomena need to be recognized and duly addressed:

- *Cake formation*. This results from the balance of forces (shear stress at the membrane wall and filtration force) and is evidently linked to the biomass characteristics.
- *Blockage of bundle of fibers*. The bundle of fibers act as a deep bed filter (depending on biomass characteristics and structure of the bundle).
- *Biofilm formation*. This is not strictly dependent upon biomass characteristics as, very often, the microorganisms involved in the biofilm formation are not the dominant species in the biomass.

4.16.4.7.1 Fouling development

Zhang *et al.* (2006a) proposed a three-stage history for membrane fouling in MBRs:

- *Stage 1*. An initial short-term rise in TMP due to conditioning.
- *Stage 2*. Long-term rise in TMP, either linear or weakly exponential.
- *Stage 3*. A sudden rise in TMP, with a sharp increase in dTMP/d*t*, also known as the TMP jump.

When operating at fluxes well below the apparent critical flux of the MLSS, a slow steady rise in TMP (stage 2) is observed which eventually changes to a rapid rise in TMP (stage 3). For sustainable operation, the aim would be to limit the extent of stage 1, prolong stage 2, and avoid stage 3, since it could be difficult to restore.

4.16.4.7.2 Types of membrane fouling

Definitions based on ease of removal and a variety of confusing terminologies have been proposed in the literature to describe fouling. For example, based on the ease of removal, some authors prefer to use the term 'irreversible fouling' to the fouling that can be removed by chemical cleaning but not by physical cleaning. Recently, Meng *et al.* (2009) proposed a somewhat changed definition and used the terms 'removable' and 'irremovable' for the fouling which is easily eliminated and which requires chemical cleaning, respectively. This chapter, however, uses the more direct terms – physically removable fouling and chemically removable fouling.

The formation of a cake layer which can be described as a porous media with a complex system of interconnected interparticle voids has been reported as the major contributor to membrane fouling in MBRs (Jeison and van Lier, 2007; Ramesh *et al.*, 2007). Such fouling is usually physically removable. Recently, a large number of scientific investigations have been performed in order to gain a better understanding of cake-layer formation and cake-layer morphology employing techniques such as confocal laser-scanning microscopy (CLSM), multiphoton microscopy, etc. (Yang *et al.*, 2007; Hughes *et al.*, 2006, 2007).

During initial filtration, colloids, solutes, and microbial cells pass through and deposit inside the membrane pores. However, during the long-term operation of MBRs, the deposited cells multiply and yield extracellular polymeric substance (EPS), which clog the pores and form a strongly attached fouling layer. Chemical cleaning is usually required to remove such fouling. Evaluation of physically removable and chemically removable fouling propensity of MBR mixed liquor has been the focus of many studies to date (Field *et al.*, 1995; Ognier *et al.*, 2004; Pollice *et al.*, 2005; Bacchin *et al.*, 2006; Guglielmi *et al.*, 2007; Lebegue *et al.*, 2008; Wang *et al.*, 2008b).

Some of the definitions are based on the fouling components. The fouling in MBRs can be classified into three major categories: biofouling, organic fouling, and inorganic fouling, although, in general, all of them take place simultaneously during membrane filtration of activated sludge. Biofouling refers to the deposition, growth, and metabolism of bacteria cells or flocs on the membranes. Biofouling may start with the deposition of individual cell or cell cluster on the membrane surface, after which the cells multiply and form a biocake (Liao *et al.*, 2004; Pang *et al.*, 2005; Wang *et al.*, 2005; Ramesh *et al.*, 2007). Techniques such as scanning electron microscopy (SEM), CLSM, atomic force microscopy (AFM), and direct observation through the membrane (DOTM) have been extensively used to derive valuable information regarding floc/cell-deposition process and the microstructure or architecture of the cake layer. Certain studies have also analyzed the microbial community structures and microbial colonization on the membranes in MBRs (Chen *et al.*, 2004; Jin *et al.*, 2006; Jinhua *et al.*, 2006; Zhang *et al.*, 2006b; Miura *et al.*, 2007; Lee *et al.*, 2009) employing molecular techniques. Such studies reported that the microbial communities on membrane surfaces were quite different from those in the suspended biomass and initially a specific phylogenetic group of bacteria may play the key role in development of the mature biofilm. However, a temporal change

of microbial-community structure can take place due to the development of anoxic conditions in the cake layer.

Organic fouling in MBRs refers to the deposition of biopolymers on the membranes (Meng *et al.*, 2009). Due to the small size, the soluble biopolymers can be deposited onto the membranes more readily, but they have lower back-transport velocity in comparison to large particles (e.g., colloids and sludge flocs). Powerful analytical tools such as Fourier transform infrared (FTIR) spectroscopy, solid-state ^{13}C-nuclear magnetic resonance (NMR) spectroscopy, and high-performance size-exclusion chromatography (HP-SEC) are usually utilized for identification of the deposited biopolymers (Kimura *et al.*, 2005; Rosenberger *et al.*, 2006; Zhou *et al.*, 2007; Teychene *et al.*, 2008) and studies have confirmed that SMP or EPS is the origin of organic fouling in MBR.

Inorganic elements such as Mg, Al, Fe, Ca, Si, etc. and metals can enhance the formation of biofouling and organic fouling and can together form a recalcitrant cake layer (Lyko *et al.*, 2007; Wang *et al.*, 2008b). Inorganic fouling can form in two ways – due to concentration-polarization-led chemical precipitation and entrapment within biopolymer gel layer (Meng *et al.*, 2009). Chemical cleaning agents such as ethylenediaminetetraacetic acid (EDTA) might efficiently remove inorganics on the membrane surface (Al-Amoudi and Lovitt, 2007); however, the fouling caused by inorganic scaling may not be easy to eliminate even by chemical cleaning (You *et al.*, 2006).

4.16.4.7.3 Parameters influencing MBR fouling

All the parameters involved in the design and operation of MBR processes have an influence on membrane fouling (Le-Clech *et al.*, 2006; Meng *et al.*, 2009). While some of these parameters have a direct influence on MBR fouling, many others result in subsequent effects on phenomena exacerbating fouling propensity. However, three main categories of factors can be identified – membrane and module characteristics, feed and biomass parameters, and operating conditions.

Figure 8 lists the membrane-fouling parameters, while Figure 9 illustrates the interrelations and combined effect of those parameters.

Some of the membrane characteristics and the parameters that influence the performance of the MBRs are discussed in the following:

1. *Physical parameters.*

- *Pore size and distribution*. Studies revealed that the pore size alone could not predict hydraulic performances. The effects of pore size (and distribution of pore size) on membrane fouling are strongly related to the feed-solution characteristics and in particular the particle-size distribution. The complex and changing nature of

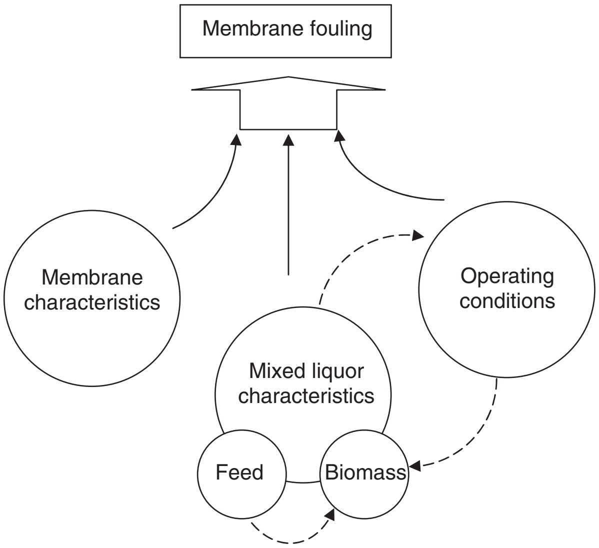


Figure 9 Interrelations and combined effect of the membrane fouling parameters.

Membrane characteristics	Feed–biomass characteristics	Operating conditions
• Physical parameters -Pore size and distribution -Porosity/roughness -Membrane configuration • Chemical parameters -Hydrophobicity -Materials	• Nature of feed and concentration • Biomass fractionation • Biomass (bulk) parameters -MLSS concentration -Viscosity -Temperature -Dissolved oxygen (DO) • Floc characteristics -Floc size -Hydrophobicity/surface charge • Extracellular polymeric substance (EPS) • Soluble microbial products (SMP)	• Aeration, cross-flow velocity • Sludge retention time (SRT) • Unsteady state operation

Figure 8 Membrane fouling parameters at a glance.

the biological suspension present in MBR systems and the large pore-size distribution of the membrane generally used in MBR systems are the main reasons for the undefined general dependency of the flux propensity on pore size (Chang *et al.*, 2002a; Le-Clech *et al.*, 2003b). It is generally expected that smaller-pore membranes would reject a wider range of materials, and the resulting cake layer would feature a higher resistance compared to large-pore membranes. However, this type of fouling is easily removed during the maintenance cleaning than fouling due to internal pore clogging obtained in larger-pore membrane systems. The chemically removable fouling, due to the deposition of organic and inorganic materials onto and into the membrane pores, is the main cause of the poor long-term performances of larger pore-size membranes (Chang *et al.*, 2001; He *et al.*, 2005). However, the opposite trend is sometimes reported (Gander *et al.*, 2000). The duration of the experiment and other operating parameters such as cross-flow velocity and constant pressure or constant flux operation have a direct influence on the determination of the optimization of the membrane pore size and are responsible for contradictory reports in the literature.

- *Porosity/roughness*. Membrane roughness and porosity along with membrane microstructure, material, and pore-size distribution were suggested as potential reasons for the different fouling behaviors observed (Kang *et al.*, 2006; Ho and Zydney, 2006). For instance, a track-etched membrane, with its dense structure and small but uniform cylindrical pores, featured the lowest resistance due to pore fouling in contrast to the other membranes having interwoven sponge-like highly porous network (Fang and Shi, 2005). Other studies have pointed out the importance of pore-aspect ratio (mean major-axis length/mean minor-axis length) (Kim *et al.*, 2004) or roughness (He *et al.*, 2005) on fouling in an MBR.
- *Membrane configuration*. In submerged MBR processes, the membrane can be configured as vertical flat plates, vertical or horizontal hollow fine fibers (filtration from out to in) or, more rarely as tubes (filtration from in to out). Each of hollow-fiber and flat-sheet membrane types has specific footprint and air scouring and chemical cleaning requirement, which may favor one process over another for a given application (Judd, 2002; Hai *et al.*, 2005). Nevertheless, hollow-fiber modules are generally more economical to manufacture, provide high specific membrane area, and can tolerate vigorous backwashing (Stephenson *et al.*, 2000). For low-flux operation, hollow fibers are attractive due to their high packing density. A higher fiber-packing density would increase productivity; however, increasing the packing density may lead to severe interstitial blockage due to the impeded propagation of air bubbles toward the core, limiting their effect on fouling limitation (Kiat *et al.*, 1992; Yeo and Fane, 2005; Sridang *et al.*, 2005). However, Hai *et al.* (2008a) developed a spacer-filled module in order to utilize high packing density without encountering severe fouling. Studies have also revealed the effects of other membrane characteristics including hollow-fiber orientation, size, and flexibility (Cui *et al.*, 2003; Ognier *et al.*, 2004; Chang and Fane, 2002; Lipnizki and Field, 2001; Zheng *et al.*, 2003; Zhongwei *et al.*, 2003).

2. *Chemical parameters.*

- *Hydrophobicity.* The influence of the membrane hydrophobicity on the early stage of the fouling formation may be significant; however, this parameter is expected to play only a minor role during extended filtration periods in MBRs (Le-Clech *et al.*, 2006). Once initially fouled, the membrane's chemical characteristics would become secondary to those of the sludge materials covering the membrane surface. Nevertheless, because of the hydrophobic interactions occurring between solutes, microbial cells and membrane material, membrane fouling is expected to be more severe with hydrophobic rather than hydrophilic membranes (Madaeni *et al.*, 1999; Chang *et al.*, 1999; Yu *et al.*, 2005a), although different results have also been reported (Fang and Shi, 2005). In many reported studies, change in membrane hydrophobicity often occurs with other membrane modifications such as pore size and morphology, which make the correlation between membrane hydrophobicity and fouling more difficult to assess.
- *Materials*. The large majority of the membranes used in MBRs are polymeric based. A direct comparison between polyethylene (PE) and polyvinylidene fluoride (PVDF) membranes clearly indicated that the latter leads to a better prevention of physically irremovable fouling and that PE membrane fouled more quickly (Yamato *et al.*, 2006). Zhang *et al.* (2008b) studied the affinity between EPS and the three polymeric UF membranes, and observed that the affinity capability of the three membranes was of the order polyacrylonitrile (PAN) < PVDF < polyethersulfone (PES). Although featuring superior chemical, thermal, and hydraulic resistances, ceramic (Fan *et al.*, 1996; Scott *et al.*, 1998; Luonsi *et al.*, 2002; Xu *et al.*, 2003; Judd *et al.*, 2004) and stainless steel (Zhang *et al.*, 2005) membrane modules are not the preferred option for MBR applications due to their high cost (around an order of magnitude more expensive than the polymeric materials).

3. *Feed–biomass characteristics.*

- *Nature of feed and concentration.* Fouling in the MBR is mostly affected by the interactions between the membrane and the biological suspension rather than wastewater itself (Choi *et al.*, 2005). Nevertheless, the fouling propensity of the wastewater has to be indirectly taken into consideration during the characterization of the biomass, as the wastewater nature can significantly influence the physicochemical changes in the biological suspensions (Le-Clech, 2003b; Jefferson *et al.*, 2004), which in turn may aggravate fouling.

- *Biomass fractionation*. The many studies (Bae and Tak, 2005; Li *et al.*, 2005a; Itonga *et al.*, 2004; Lee *et al.*, (2003); Lee *et al.*, 2001a; Wisniewski and Grasmick, 1998; Bouhabila *et al.*, 2001) that are available on the contribution of different fractions of the biomass to fouling usually report contradictory results. Although the relatively low fouling role played by the suspended solids (biofloc and the attached EPS) compared to those of the soluble and colloids (generally defined as soluble microbial products or SMP) is usually reported, the reported relative contribution of the SMP to overall membrane fouling ranges from 17% (Bae and Tak, 2005) to 81% (Itonga *et al.*, 2004). These wide discrepancies may be explained by the different operating conditions and biological states of the suspension used in the reported studies (**Figure 10**). Although an interesting approach for studying MBR fouling, the fractionation experiments neglect any coupling or synergistic effects which may occur among the different components of the biomass.

4. *Biomass (bulk) parameters*.

- *MLSS concentration*. Although the increase in MLSS concentration has often been reported to have a mostly negative impact on the MBR hydraulic performances (Cicek *et al.*, 1999b; Chang and Kim, 2005), controversies exist (Defrance and Jaffrin, 1999; Hong *et al.*, 2002; Le-Clech *et al.*, 2003b; Lesjean *et al.*, 2005; Brookes *et al.*, 2006). The existence of threshold values above (Lubbecke *et al.*, 1995) or below (Rosenberger *et al.*, 2005) which the MLSS concentration has a negative influence was also reported. **Figure 11** depicts the influence of shift in MLSS concentration on flux as reported in different studies. Nowadays, information on additional biomass characteristics (e.g., composition and concentration of EPS) is deemed necessary to furnish a comprehensive picture. On the other hand, Hai *et al.* (2006a)showed that the extent of fouling was independent of MLSS concentration itself, and was rather more influenced by the efficiency of the fouling-prevention strategies adopted.
- *Viscosity*. The importance of MLSS viscosity is that it modifies bubble size and can dampen the movement of hollow fibers in submerged bundles (Wicaksana *et al.*, 2006). The net result of this phenomenon would be a greater rate of fouling. Increased viscosity also reduces the efficiency of mass transfer of oxygen and can therefore effect dissolved oxygen (DO) (Germain and Stephenson, 2005); fouling, as discussed later, tends to be worse at low DO. Critical MLSS concentrations have been reported in the literature (Itonga *et al.*, 2004) above which, suspension viscosity tends to increase exponentially with the solid concentration.
- *Temperature*. Experiments conducted under moderate temperature usually report greater deposition of materials on the membrane surface at lower temperatures. Temperature may impact membrane filtration by increasing fluid viscosity, causing defloculation of biomass and higher EPS secretion, reducing biodegradation rate, etc. (Jiang *et al.*, 2005; Rosenberger *et al.*, 2006).
- *Dissolved oxygen*. The effects of DO on MBR fouling are multiple and may include changes in biofilm structure, SMP levels, and floc-size distribution (Lee *et al.*, 2005). The average level of DO in the bioreactor is controlled by the aeration rate, which not only provides oxygen to the biomass but also tends to limit fouling formation on the membrane surface. Optimum aeration would result in lower specific cake resistance of the fouling layer featuring larger particle sizes and greater porosity (Kang *et al.*, 2003; Kim *et al.*, 2006). Therefore, in general, higher DO tends to lead to better filterability, and lower fouling rate.

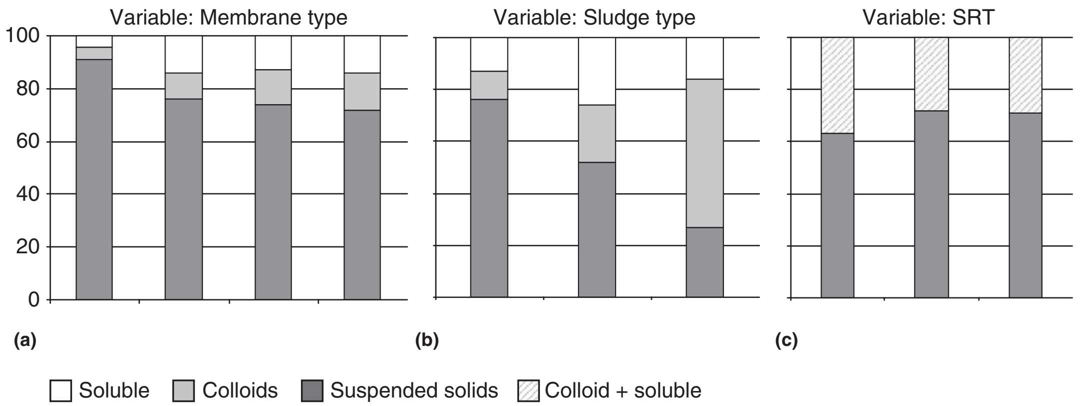


Figure 10 Influence of different parameters (membrane type, sludge type, and SRT) on the relative contributions (in %) of the different biomass fractions to MBR fouling. Data from (a) Bae TH and Tak TM (2005) Interpretation of fouling characteristics of ultrafiltration membranes during the filtration of membrane bioreactor mixed liquor. *Journal of Membrane Science* 264: 151–160; (b) Meng F and Yang F (2007) Fouling mechanisms of deflocculated sludge, normal sludge, and bulking sludge in membrane bioreactor. *Journal of Membrane Science* 305: 48–56; and (c) Lee W, Kang S, and Shin H (2003) Sludge characteristics and their contribution to microfiltration in submerged membrane bioreactors. *Journal of Membrane Science* 216: 217–227.

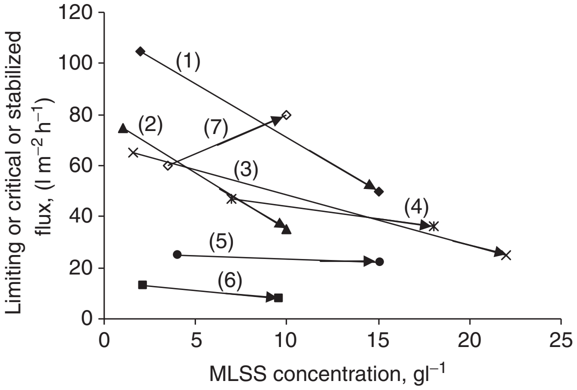


Figure 11 Influence of shift in MLSS concentration on flux (fouling) as reported in different studies. Data from (1) Cicek N, Franco JP, Suidan MT, and Urbain V (1998) Using a membrane bioreactor to reclaim wastewater. *Journal of American Water Works Association* 90: 105–113; (2) Beaubien A, Baty M, Jeannot F, Francoeur E, and Manem J (1996) Design and operation of anaerobic membrane bioreactors: Development of a filtration testing strategy. *Journal of Membrane Science* 109: 173–184; (3) Madaeni SS, Fane AG, and Wiley D (1999) Factors influencing critical flux in membrane filtration of activated sludge. *Journal of Chemical Technology and Biotechnology* 74: 539–543; (4) Han SS, Bae TH, Jang GG, and Tak TM (2005) Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system. *Process Biochemistry* 40: 2393–2400; (5) Bouhabila EH, Ben Aim R, and Buisson H (1998) Microfiltration of activated sludge using submerged membrane with air bubbling (application to wastewater treatment). *Desalination* 118: 315–322; (6) Bin C, Xiaochang W, and Enrang W (2004) Effects of TMP, MLSS concentration and intermittent membrane permeation on a hybrid submerged MBR fouling. In: *Proceedings of the IWA – Water Environment – Membrane Technology (WEMT) Conference.* Seoul, Korea, 7–10 June; and (7) Defrance L and Jaffrin MY (1999) Reversibility of fouling formed in activated sludge filtration. *Journal of Membrane Science* 157: 73–84.

5. *Floc characteristics.*

- *Floc size.* The floc-size distribution obtained with the MBR sludge is lower than the results generally obtained from CASP (Zhang *et al.*, 1997; Wisniewski and Grasmick, 1998; Lee *et al.*, 2003; Cabassud *et al.*, 2004; Bae and Tak, 2005). Unlike in the CAS systems, the effective separation of suspended biomass from the treated water is not critically dependent on aggregation of the microorganisms, and the formation of large floc. However, independent of their size, biological floc play a major role in the secretion of EPS and formation of the fouling cake on the membrane surface.
- *Hydrophobicity/surface charge.* The direct effect of floc hydrophobicity on MBR fouling is difficult to assess. Conceptually, hydrophobic flocs would lead to high flocculation propensity, less secretion of EPS, and low interaction with the hydrophilic membrane (Jang *et al.*, 2006). However, reports of highly hydrophobic flocs fouling MBR membranes can be found in the literature. For instance, the excess growth of filamentous bacteria, known to be responsible for severe MBR fouling, also resulted in higher EPS levels, lower zeta potential, more irregular floc shape, and higher hydrophobicity (Meng *et al.*, 2006).

6. *Extracellular polymeric substances.*

   The term EPS is used as a general and comprehensive concept for different classes of macromolecules such as polysaccharides, proteins, nucleic acids, (phosphor-)lipids, and other polymeric compounds which have been found at, or outside, the cell surface and in the intercellular space of microbial aggregates (Flemming and Wingender, 2001). EPS are the construction materials for microbial aggregates such as biofilms, flocs, and activated sludge liquors. The functions of EPS matrix are multiple and include aggregation of bacterial cells in flocs and biofilms, formation of a protective barrier around the bacteria, retention of water, and adhesion to surfaces (Laspidou and Rittmann, 2002). With its heterogeneous and changing nature, EPS can form a highly hydrated gel matrix in which microbial cells are embedded (Nielson and Jahn, 1999). Therefore, they can be responsible for the creation of a significant barrier to permeate flow in the membrane processes. Contemporary literature is replete with reports identifying EPS as a major fouling parameter (Chang and Lee, 1998; Cho and Fane, 2002; Nagaoka *et al.*, 1996, 1998; Rosenberger and Kraume, 2002). On the other hand, since the EPS matrix plays a major role in the hydrophobic interactions among microbial cells and thus in the floc formation (Liu and Fang, 2003), it was proposed that a decrease in EPS levels may cause floc deterioration and may be detrimental for the MBR performances. This indicates the existence of an optimum EPS level for which floc structure is maintained without featuring high fouling propensity. Many parameters including gas sparging, substrate composition (Fawehinmi *et al.*, 2004), and loading rate (Cha *et al.*, 2004; Ng *et al.*, 2005) affect EPS characteristics in the MBR, but SRT probably remains the most significant of them (Hernandez *et al.*, 2005). A functional relationship between specific resistance, mixed liquor volatile suspended solids (MLVSS), TMP, and permeate viscosity, and EPS is believed to exist (Cho *et al.*, 2005).

7. *Soluble microbial products.* SMPs are defined as soluble cellular components that are released during cell lysis, diffuse through the cell membrane, and are lost during synthesis or are excreted for some purpose (Laspidou and Rittmann, 2002; Li *et al.*, 2005a). During filtration, SMPs adsorb on the membrane surface, block membrane pores, and/or form a gel structure on the membrane surface where they provide a possible nutrient source for biofilm formation and a hydraulic resistance to permeate flow (Rosenberger *et al.*, 2005). Since direct relationships between the carbohydrate level in SMP (SMPc) solution with fouling rate (Lesjean *et al.*, 2005), filtration index and capillary suction time (CST) (Greiler *et al.*, 2005; Evenblij *et al.*, 2005b; Tarnacki *et al.*, 2005), critical flux tests (Le-Clech *et al.*, 2005b), and specific flux (Rosenberger *et al.*, 2005) have been clearly described, it reveals SMPc to be the major foulant indicator in MBR systems. However, controversy over the relative contribution of carbohydrate and protein portions of SMP to fouling exists (Evenblij and Van der Graaf, 2004; Drews *et al.*, 2005a; Drews *et al.*, 2006).

The operating conditions of MBrs are discussed as follows:

- *Aeration, cross-flow velocity*. Since the origin of the SMBR, bubbling has been defined as the strategy of choice to induce flow circulation and shear stress on the membrane surface. Aeration used in MBR systems has three major roles: providing oxygen to the biomass, maintaining the activated sludge in suspension, and mitigating fouling by constant scouring of the membrane surface (Dufresne *et al.*, 1997). However, an optimum aeration rate, beyond which a further increase has no significant effect on fouling suppression, has been observed on many occasions (Ueda *et al.*, 1997; Le-Clech *et al.*, 2003a, 2003b; Liu *et al.*, 2003; Psoch and Schiewer, 2005b). It is also important to note that too intense an aeration rate may damage the floc structure reducing their size, and release EPS into the bioreactor (Park *et al.*, 2005; Ji and Zhou, 2006), and thereby aggravate fouling.
- *Solid retention time*. SRT (and thereby the F/M ratio), which greatly controls biomass characteristics, is regarded as the most important operating parameter influencing fouling propensity in MBRs. Considering the advantages of this process over the conventional activated sludge process (CASP), the early MBRs were typically run at very long SRTs to minimize excess sludge (Liu *et al.*, 2005; Gao *et al.*, 2004; Nuengjamnong *et al.*, 2005). But unlike in bench-scale studies employing simpler synthetic feed, the progressive accumulation of nonbiodegradable materials (such as hair and lint) in an MBR fed with real sewage definitely leads to clogging of the membrane module (Le-Clech *et al.*, 2005b). Operating an MBR at higher SRT leads inevitably to increase of MLSS concentration (Zhang *et al.*, 2006c). The increase in aeration intensity to retain high MLSS levels in suspension and maintain proper oxygenation may not be a sustainable option for the treatment process. In this scenario, the increased shear provided to control fouling could cause biofloc deterioration as well as cell lysis and enhanced EPS secretion, and lead to fatal fouling. On the other hand, at infinite SRT, most of the substrate is consumed to ensure the maintenance needs and the synthesis of storage products. The very low apparent net biomass generation observed can explain the low fouling propensity observed for high SRT operation in certain studies (Orantes *et al.*, 2004). It is likely that there is an optimal SRT, between the high fouling tendency of very low SRT operation and the high viscosity suspension prevalent for very long SRT.
- *Unsteady state operation*. In practical applications, unsteady state conditions such as variations in operating conditions (flow input/HRT and organic load) and shifts in oxygen supply could occur regularly (Drews *et al.*, 2005a). The start-up phase can also be considered as unsteady operation and data collected before biomass stabilization (including the period necessary to reach acclimatization) may become relevant in the design of MBRs (Cho *et al.*, 2005). Such unsteady state conditions have also been defined as additional factors leading to changes in MBR fouling propensity. For instance, the addition of a spike of acetate in the feedwater significantly decreased the filterability of the biomass in an MBR due to the rise in SMP levels resulting from the feed spike (Evenblij *et al.*, 2005a).

4.16.4.7.4 Fouling mitigation

The complex interactions between the fouling parameters complicate the perception of MBR fouling and it is therefore crucial to have a complete understanding of the biological, chemical, and physical phenomena occurring in MBRs to assess fouling propensity and mechanisms and thereby formulate mitigation strategies. As membrane fouling increases with increasing flux in all membrane separation processes, the operating flux should be lower than the critical flux. When the operating flux is below the critical flux, particle accumulation in the region of membranes can be effectively prevented. However, due to physicochemical solute–membrane material interactions, the membrane permeability decreases over time, even when MBRs are operated in subcritical (below critical flux) conditions. Other preventative methods need to be considered to maintain stable operation of MBR systems (Figure 12).

Fouling can be removed by various methods and they are as discussed herein:

1. *Physical cleaning*.

   The following methods are usually used in combination to remove membrane fouling:

   - *Permeate backwashing*. Membrane backwashing or backflushing refers to pumping permeate in the reverse direction through the membrane. Backwashing has been found to successfully remove most of the reversible fouling due to pore blocking, transport it back into the bioreactor, and partially dislodge loosely attached sludge cake from the membrane surface (Bouhabila *et al.*, 2001; Psoch and Schiewer, 2005a; Psoch and Schiewer, 2006). Frequency, duration, the ratio between those two parameters, and its intensity are the key parameters in the design of backwashing and different combinations of these parameters have proved to be more efficient in different studies (Jiang *et al.*, 2005; Schoeberl *et al.*, 2005). Between 5% and 30% of the produced permeate is used for backwashing. This also

Removal of fouling	Limitation of fouling
• Physical cleaning --Backwashing --Air backwashing --Intermittent operation --Sonification and other energy-intensive processes • Chemical cleaning --Maintenance cleaning --Intensive cleaning	• Optimization of membrane characteristics • Optimization of operating conditions --Aeration --Other operating conditions --Membrane module design • Modification of biomass characteristics -Aerobic granular sludge -Coagulant/flocculent -Adsorbent/flux enhancers

Figure 12 Reported membrane fouling mitigation strategies at a glance.

affects operating costs as, obviously, energy is required to achieve a pressure suitable for flow reversion. Certain studies are, therefore, devoted to optimization of backwashing (Smith *et al.*, 2005).

- *Air backwashing*. Air, instead of permeate, can also be used as the backflushing medium (Visvanathan *et al.*, 1997; Sun *et al.*, 2004). The invention of air backwashing techniques for membrane declogging led to the development of using the membrane itself as both clarifier and air diffuser. In this approach, two sets of membrane modules are submerged in the aeration tank. While the permeate is extracted through one of the sets, the other is supplied with compressed air for backwashing. The cycle is repeated alternatively, and there is a continuous airflow into the aeration tank, which is sufficient to aerate the mixed liquor. However, air backwashing may also present potential issues of membrane breakage and rewetting (Le-Clech *et al.*, 2006).
- *Intermittent operation*. Intermittent operation or membrane relaxation can significantly improve membrane productivity (Yamamoto *et al.*, 1989). During relaxation, back transport of foulants is naturally enhanced as loosely attached foulants can diffuse away from the membrane surface (Ng *et al.*, 2005). Although some studies found it more important than backwashing for fouling removal (Schoeberl *et al.*, 2005), recent studies tend to combine intermittent operation with frequent backwashing for optimum results (Zhang *et al.*, 2005; Vallero *et al.*, 2005). The economic feasibility of intermittent operation for large-scale MBRs has been the focus of certain studies (Hong *et al.*, 2002); however, it seems rather an established operation mode nowadays.
- *Sonification and other energy-intensive processes*. Although sonification would be difficult to apply at a large scale due to the focused nature of the sonic energy, laboratory-scale studies have explored sonification for breaking down cake layers in MBRs, especially in case of ceramic membranes. Certain studies have confirmed the efficiency of application of sonification alone or in combination with backwashing for removing the cake layer (Lim and Bai, 2003; Fang and Shi, 2005). However, other studies report that fouling may even worsen due to pore blocking (Hai *et al.*, 2006a). Attempts have also been made to control fouling or modify sludge by using ozone and electric field (Chen *et al.*, 2007; Huang and Wu, 2008; Sui *et al.*, 2008; Wen *et al.*, 2008).

2. *Chemical cleaning*. The effectiveness of physical cleaning tends to decrease with operation time as more recalcitrant fouling accumulates on the membrane surface. Therefore, in addition to physical cleaning, different types/intensities of chemical cleaning are applied in practice. A combination of the following types of cleaning is usually applied (Le-Clech *et al.*, 2006):

   - Maintenance cleaning with moderate chemical concentration (weekly) is applied to maintain design permeability and it helps to reduce the frequency of intense cleaning. This may be replaced by a more frequent (e.g., on a daily basis) chemically enhanced backwash utilizing mild chemical concentration.
   - Intensive (or recovery) chemical cleaning (once or twice a year) is generally carried out when further filtration is no longer sustainable because of an elevated TMP.

The MBR suppliers propose their own chemical cleaning recipes, which differ mainly in terms of concentration and methods, and often site-specific protocols are followed (Kox, 2004; Tao *et al.*, 2005; Le-Clech *et al.*, 2005b). Mainly, sodium hypochlorite (for organic foulants) and citric acid (for inorganics) are used as chemical agents.

Some pitfalls of chemical cleaning are worth noting. The detrimental effect of cleaning chemicals on biological performance has been reported (Lim *et al.*, 2005; Hai *et al.*, 2007). It has also been mentioned that the level of pollutants (measured as TOC) in the permeate rises just after the chemical cleaning step (Tao *et al.*, 2005). This raises concern especially in case of MBRs used in the reclamation process trains (i.e., e.g., upstream of RO) (Le-Clech *et al.*, 2006). Chemical cleaning may also shorten the membrane lifetime and disposal of spent chemical agents causes environmental problems (Yamamura *et al.*, 2007).

The measures to limit fouling are discussed next.

Recently, there have been a significant number of studies which focused on the ways to limit fouling. The proposed strategies include (1) improving the antifouling properties of the membrane, (2) operating the MBR under specific non-or-little-fouling conditions, and/or (3) pretreating the biomass suspension to limit its fouling propensity. They are discussed as follows:

1. *Membrane modification*.

   - *Optimization of membrane characteristics*. Many studies have shown that chemical modifications of the membrane surface can efficiently improve antifouling properties. Recent examples comprise (1) increasing membrane hydrophilicity by NH_3 and CO_2 plasma treatments (Yu *et al.*, 2005a, 2005b) and ultraviolet (UV) irradiation (Yu *et al.*, 2007), (2) TiO_2 entrapped membrane (Bae and Tak, 2005), and (3) applying precoating of TiO_2 (Bae *et al.*, 2006), GAC (Hai, 2007), ferric hydroxide (Zhang *et al.*, 2004), polyvinylidene fluoride-graft-polyoxyethylene methacrylated (PVDF-g-POEM) (Asatekin *et al.*, 2006), polyvinyl alcohol (PVA) (Zhang *et al.*, 2008a), etc. Improved performance in case of precoated membrane has been attributed to the adsorption of soluble organics on the precoat, limiting the direct contact between the organics and the membrane. Self-forming dynamic membrane-coupled bioreactors, utilizing coarse pore-sized substrates and allowing cake and gel layers to deposit on the surface, have been reported to obtain high flux and good removal in certain studies, although stable performance cannot be expected with such a filtration barrier (Wu *et al.*, 2004).
   - *Membrane module design*. The membrane module design by optimizing the packing density of hollow fibers or flat sheets, the location of aerators, the orientation of

fibers, and diameters of fibers (Chang and Fane, 2001; Chang *et al.*, 2002b; Fane *et al.*, 2002) remains another important parameter in the optimization of the MBR operation. In a specially designed module in which air bubbles were confined in close proximity to the hollow fiber (rather than diffusing in the reactor), higher permeability was obtained (Ghosh, 2006). Two major design approaches are adopted in case of the commercially available hollow-fiber bundles. One of these approaches relies on partitioning of bundles of fibers, which are fixed at both ends, to secure flow path of air bubbles introduced from the center of the bundle at the base, thereby leading sludge out of the module. In another approach, bundle of one-end free fibers are allowed to float freely under the scouring action of air bubbles introduced from the core of the bundle to avoid accumulation of sludge. In order to utilize high packing density without encountering severe fouling, a new approach to hollow-fiber module design was explored by Hai *et al.* (2008a). Spacer was introduced within usual hollow-fiber bundles with the aim of minimizing the intrusion of sludge into the module. The little amount of intruded sludge was then backwashed through the bottom end, while the sludge deposited on the surface was effectively cleaned by air scouring. In this way, efficient utilization of cleaning solution and air for backwashing and surface cleaning, respectively, were possible.

Recent approaches such as novel fiber sheet (FiSh) membrane (Heijnen *et al.*, 2009), multimodule flat-sheet concept (Kreckel *et al.*, 2009), and vacuum rotation membrane (Alnaizy and Sarin, 2009; Komesli *et al.*, 2007) are also noticeable.

2. *Optimization of operating conditions.*

- *Aeration*. As mentioned earlier, bubbling is an established strategy to induce flow circulation and shear stress on the membrane surface. The aeration intensity (air/permeate ratio, m^3/m^3) applied by MBR suppliers may vary between 24 and 50, depending on the membrane configuration (flat sheet vs. hollow fiber) and the MBR tank design (whether the membrane and aerobic zone combined into a single tank or not) (Tao *et al.*, 2005; Le-Clech *et al.*, 2006). However, recent large-scale studies revealed these original ratios to be quite conservative (Tao *et al.*, 2005). The specific design of bubble size, airflow rate and patterns, and location of aerators have been defined as crucial parameters in fouling mitigation. As the energy involved in providing aeration to the membrane remains a significant cost factor in MBR design, efforts have been focused on optimization of aeration both from the points of view of fouling mitigation and reducing energy requirement. Recent developments in aeration design include cyclic aeration systems (Rabie *et al.*, 2003), intermittent aeration (Yeom *et al.*, 1999; Nagaoka and Nemoto, 2005), air pulsing (Judd *et al.*, 2006), air sparging (Ghosh, 2006), improved aerator systems (Miyashita *et al.*, 2000; Cote, 2002; Hai *et al.*, 2008), etc.
- *Other operating conditions.* The overall performance of the MBR is closely related to the choice of SRT value. Further optimizations of operating conditions through reactor design have been studied and include the addition of a spiral flocculator (Guo *et al.*, 2004), vibrating membranes (Genkin *et al.*, 2005), helical baffles (Ghaffour *et al.*, 2004), suction mode (Kim *et al.*, 2004) and high-performance compact reactor (Yeon *et al.*, 2005), novel types of air lift (Chang and Judd, 2002), porous and flexible suspended membrane carriers (Yang *et al.*, 2006), and the sequencing batch MBR (Zhang *et al.*, 2006d). A reasonable flux rate without significant fouling is ideally expected. The concept of sustainable flux in MBRs was introduced from this point of view (Ng *et al.*, 2005).

3. *Modification of biomass characteristics.*

- *Aerobic granular sludge.* In order to obtain higher biological aggregates in the bioreactor, aerobic granular sludge has also been used in MBR systems (Li *et al.*, 2005b). With an average size around 1 mm, granular sludge increased the membrane permeability by 50%, but lower cleaning recoveries were observed (88% of those obtained with a conventional MBR). Such granular sludge may also not be stable under long-term operation (Hai, 2007).
- *Coagulant/flocculant*. Due to back transport and shear-induced fouling control mechanisms, large microbial flocs are expected to have a lower impact on membrane fouling. Based on this expectation, studies have explored addition of coagulants such as alum (Holbrook *et al.*, 2004), ferric chloride, zeolite (Lee *et al.*, 2001b), chitosan (Ji *et al.*, 2008), etc. and have shown permeability enhancement. Pretreatment of the effluent is also possible and studies based on the pre-coagulation/sedimentation of effluent before its introduction in the bioreactor revealed the fouling limitation offered by this technique (Itonga and Watanabe, 2004; Le-Clech *et al.*, 2006).
- *Adsorbent/flux enhancers*. Lower fouling propensity is observed in MBR processes when biomass is mixed with adsorbents in that addition of adsorbents into biological treatment systems decreases the level of pollutants, and more particularly organic compounds (Kim and Lee, 2003; Lesage *et al.*, 2005; Li *et al.*, 2005c; Ng *et al.*, 2006). In view of saturation of PAC during long-term studies, researchers have suggested periodic addition of PAC (Ng *et al.*, 2005; Fang *et al.*, 2006). Certain studies have proposed pre-flocculation and PAC addition (Guo *et al.*, 2004; Cao *et al.*, 2005).

A cationic polymer-based membrane performance enhancer (MPE 50) has been commercialized by Nalco recently. The interaction between the polymer and the soluble organics was reported as the main mechanism responsible for performance enhancement (Yoon *et al.*, 2005). The potential impacts of coagulants or adsorbents on biomass community or biomass metabolism need to be taken into account (Iversen *et al.*, 2009), and the discharge of some chemicals that are used as coagulants or adsorbents might be a potential environmental

risk. Such flux enhancers are probably best suited for solving occasional upsets rather than their continuous addition.

Emerging fouling monitoring/control techniques such as interference of microbial intercellular communication by enzymatic degradation of signal molecules (Kjelleberg *et al.*, 2008; Yeon *et al.*, 2009), proteins and polysaccharides sensor for online fouling control (Mehrez *et al.*, 2007), application of two-dimensional fluorescence for monitoring MBR performance (Galinha *et al.*, 2009), etc., are worth noting.

4.16.5 Worldwide Commercial Application

4.16.5.1 Installations Worldwide

The MBR process is an emerging advanced wastewater-treatment technology that has been successfully applied at an ever-increasing number of locations around the world. MBRs were first developed 40 years ago and have been used commercially in Japan for almost 30 years. Since 1990, MBR technology has been adopted in North America and Europe, and it is now experiencing rapid growth in a wide variety of applications. In Asia, the drive in Japan was followed by an enthusiastic uptake in South Korea in the 1990s, and more recently by China. The highest growth rates are found in areas of greatest water stress for reuse applications, such as the southwestern US, China, Singapore, and Australia. The low footprint of the MBR is a significant driver for developed economies.

4.16.5.1.1 Location-specific drivers for MBR applications

Howell (2004) stipulated the location-specific global drivers for MBR technology as follows:

1. *Asia*. MBR technology is being considered at many locations all over Asia, the main driver being water reclamation. Examples of settings vary from small-scale applications in Japan, where MBR product water is reused as toilet-flushing water in apartment blocks, medium-sized industrial applications in various countries, and large-scale municipal WWTPs in China.
2. *Middle East*. Clean-water shortages are the obvious driver for MBR applications in the Middle East, in treatment of both municipal as well as industrial (petrochemical) wastewater.
3. *Europe*. In Western Europe, water reclamation is not the main driver. In the UK, an important driver is compactness and strict discharge limits due to bathing wastewater requirements. In Germany and the Netherlands, important push factors are strict discharge requirements due to ecologically sensitive surface waters and the innovative character of the technological developments related to MBR. In Southern Europe, water reclamation can be considered as the main driver.
4. *Northern America*. In the US and Canada, MBR initiatives are predominantly driven by strict discharge requirements due to ecologically sensitive surface waters. At some locations, water reclamation is another important driver. In the US, where wastewater-treatment infrastructure lags behind population growth, MBRs are being increasingly implemented to make up the shortfall. Where there is limited space to locate treatment plants, MBRs offer the potential to meet the needs of communities.
5. *Australia*. Stringent effluent-quality targets and water-reuse potential are obvious drivers for drought-stricken Australia.

4.16.5.1.2 Plant size

Earlier MBR technology was favored in difficult applications or those applications where compactness was important and reuse was the target; and it usually involved smaller plants. As the demand for MBR technology grows globally, both the number of installations and the capacity of the installed plants are increasing dramatically. The most optimistic industry estimates suggest that up to 1000 new MBR plants will be built annually during the survey period. The size of the constructed plants has grown from facilities treating hundreds to thousands of gallons of wastewater per day to those treating tens of millions of gallons per day in just a few years. However, the most common capacity for current worldwide MBR installations ranges from the 50 000 gpd (200 $m^3 d^{-1}$) to 500 000 gpd systems.

The largest MBR plant in the world is set to be operational in 2010/11 in King County, Washington State. When completed, the facility will have an initial peak flow capacity of 495 000 $m^3 d^{-1}$ (average 136 000 $m^3 d^{-1}$), rising to a daily 645 000 m^3 (average 205 000 m^3) by 2040.

4.16.5.1.3 Development trend and the current status in different regions

Figure 13 shows the regional share of total MBR plants as of 2003. Next, we discusss the trend of MBR growth in the three continents, Asia, Europe, and North America.

1. *Asia*. In the 1970s sidestream technology first entered the Japanese market. By 1993, 39 of such facilities had been reported for use in sanitary and industrial applications (Aya, 1994). The application of MBR in Japan concerned

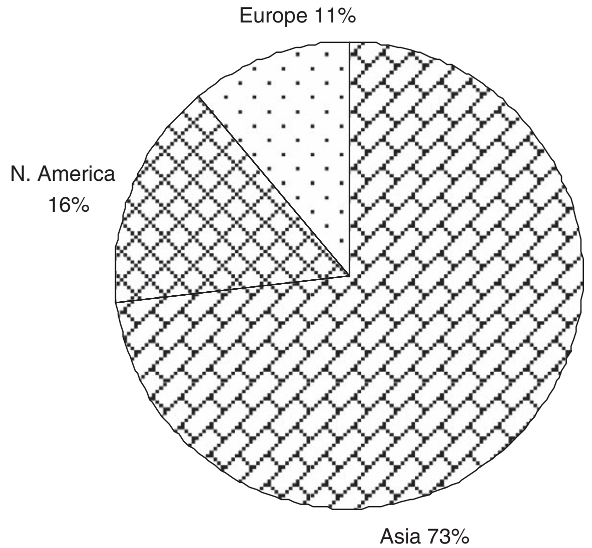


Figure 13 Regional share of total MBR plants (2003). Data from Pearce G (2008a) Introduction to membranes: An introduction to membrane.

small-scale installations for domestic wastewater treatment and reuse and some industrial applications, mainly in the food and beverage industries where highly concentrated flows are common. The domestic application often consists of so-called Johkaso or septic-tank treatment and in-building (office or domestic) wastewater-collection systems. In the early 1990s, the Japanese Government launched an ambitious 6-year research and development (R&D) project which led to a major technological and industrial breakthrough of the MBR process: the conception of submerged membrane modules, working with low negative pressure (out-to-in permeate suction), and membrane aeration to reduce fouling. This paved the way toward a significant reduction of capital and operation costs, due to the reduction and simplification of equipment and the abandonment of the energy-demanding sludge-recirculation loop. Since then, commercial MBRs proliferated in Japan, which had 66% of the world's processes in 2000 (Stephenson *et al.*, 2000). In Japan, although MBRs have long been used for industrial wastewater treatment or for reuse of wastewater in large buildings and so on, the introduction of municipal MBRs has lagged behind compared with other water-related fields. The first MBR for municipal wastewater treatment with an installed capacity of 2100 $m^3 d^{-1}$ (total design capacity 12 500 $m^3 d^{-1}$) in Japan started operation in March 2005, and this accelerated the introduction of MBRs in Japanese sewerage systems. Nine MBR plants, mostly small scale, for municipal wastewater treatment, are in operation at present (**Table 8**). In addition, there are several MBR plants currently in the design or planning stage. The number of MBRs for municipal wastewater is expected to increase in the near future and the technology will also play an important role in retrofitting and upgrading of existing treatment plants.

The MBR technology saw an enthusiastic uptake in South Korea in the 1990s following its introduction in Japan. By 2005, the number of MBR plants rose up to more than 1300 (Namkung, 2008). The plants are mostly small, with more than 60% of the total plants having a capacity of less than 50 $m^3 d^{-1}$. The plants were predominantly built on the submerged membrane technology (hollow fiber, 79%; flat sheet, 12%), while a meager 9% facilities utilized the tubular membranes in sidestream format.

China has recently emerged as a strong MBR market. Hence, it would be interesting to cast light on the specific mode of development in that country. While the first paper on MBR was published in 1991, the emergence of a number of local and overseas companies developing MBR market in China accelerated with the funding of R&D projects by the Ministry of Science and Technology (MOST) in 1996 (Wang *et al.*, 2008a). Since then, much progress has been achieved both in research and in practical applications of MBR in China. This is evident by the recent yearly publication rate of 35–40 English articles on MBR in China and the construction of a total of 254 plants for municipal (137) and industrial (117) wastewater treatment by 2008. The Chinese MBR market has the presence of a total of 33 companies or institutes, including famous overseas companies such as GE–Zenon Environmental Inc., Mitsubishi–Rayon (Japan), Toray (Japan), NOVO Environmental Technology (Singapore), and XFlow (Netherlands). Among these, only three companies provide flat-sheet MBR, and, interestingly, the worldwide renowned flat-sheet membrane provider, Kubota (Japan), was not found to be very active in the Chinese membrane market. Most of the plants in operation are medium scale or small scale in terms of treatment capacity, the number of plants with treatment capacity below 1000 $m^3 d^{-1}$ totaling 225. The largest MBR plant with a capacity of 80 000 $m^3 d^{-1}$ for municipal wastewater treatment and reuse is located in Beijing. Several other large MBR plants are also in the planning stage. Wang *et al.* (2008a) contend that the increasingly stringent discharge standards and the great need of water reclamation and reuse will further push forward the application of ever-larger municipal MBR plants in China, especially in North China which has severe water shortage.

2. *Europe*. A market survey of the European MBR industry was performed by Lesjean and Huisjes (2008). They identified MBR plants constructed up to 2005, and about 300 references of industrial applications ($>20\ m^3 d^{-1}$) and about 100 municipal WWTPs >500 p.e. were listed.

In Europe, the first full-scale MBR plant for treatment of municipal wastewater was constructed in Porlock (UK, commissioned in 1998, 3800 p.e.), soon followed by WWTPs in Büchel and Rödingen (Germany, 1999, 1000 and 3000 p.e., respectively), and in Perthes-en-Gâtinais (France, 1999, 4500 p.e.). In 2004, the largest MBR plant worldwide so far was commissioned to serve a population of 80 000 p.e. (in Kaarst, Germany). The installations thus grew from small WWTPs to very large WWTPs within a few

Table 8 Municipal MBR plants in Japan

Name of plant	*Total design capacity ($m^3 d^{-1}$)*	*Capacity at commissioning ($m^3 d^{-1}$)*	*Membrane format*	*Start of operation*
Fukusaki	12 500	2100	Flat sheet	2005
Kobuhara	240	240	Flat sheet	2005
Yusuhara	720	360	Flat sheet	2005
Okutsu	580	580	Hollow fiber	2006
Daito	2000	1000	Flat sheet	2006
Kaietsu	230	230	Hollow fiber	2007
Zyosai	1375	1375	–	2008
Heta	3200	2140	–	2008
Ooda	8600	1075	–	2009

years. Nevertheless, the favored range for MBR systems still appears to be only 100–500 $m^3 d^{-1}$ and 1000–20 000 p.e. for industrial and municipal wastewaters, respectively. The design capacity of the industrial units is more than an order of magnitude smaller than for the municipal WWTPs. Lesjean and Huisjes (2008) opined that, although the construction of very large MBR plants (> 100 000 p.e.) were recently announced with much publicity, this will remain the exception in Europe, because of the lower life-cycle costs (Lesjean *et al.*, 2004) of WWTP plants equipped with tertiary-membrane filtration (**Figure 14**). Although not representative of the market, the very large plants will attract much attention and thereby may contribute to the market expansion.

The industrial market was the pioneer in the early 1990s, whereas the municipal market took off only in 1999. In 2002, 154 MBR units could be counted, among which 85% were for industrial applications. However, taking the installed membrane surface as an indicator of market share, for the period 2003–05, the municipal sector represented 75% of the market volume. Both municipal and industrial sectors saw a sharp increase in the following years, due to the commercial success and much lower capital and operating costs. By 2005, the market growth rate was linear with at least 50 industrial units and 20 municipal plants constructed per year. This progression rate is expected to sustain in the next years or may even further accelerate owing to the evolution and implementation of European and national regulations (Lesjean *et al.*, 2006).

The survey by Lesjean and Huisjes (2008) also demonstrated the predominance of the suppliers Kubota (Japan) and GE–Zenon. Their technologies based on submerged filtration modules have been outstandingly successful since 2002. In recent years, the European market can therefore be seen as a quasi-duopoly of two non-European suppliers. In contrast, the most successful MBR technologies in the 1990s, based on sidestream configurations supplied by Wehrle, Norit X-Flow, Berghof, Rodia Orelis, etc., did not experience any significant market growth over the last 3 years. This could explain the recent move of companies such as Wehrle and Norit to develop and commercialize novel low-energy airlift MBR systems.

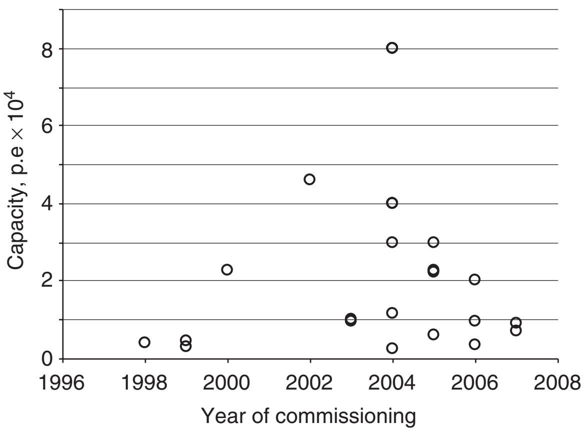


Figure 14 Plot of capacity of randomly selected European MBR plants showing predominance of medium size plants (similar trend prevails worldwide). Data from Schier W, Frechen FB, and Fischer S (2009) Efficiency of mechanical pre-treatment on European MBR plants. *Desalination* 236: 85–93.

They argued that the industrial market has become mature: the MBR is considered as the best available technology by many industries. On the other hand, the municipal market is expected to witness further growth over the next decade under the combined effects of the acceleration of plant construction and the capacity increase.

3. *North America*. Full-scale commercial applications of MBR technology in North America for treatment of industrial wastewaters dated back to 1991 (Sutton, 2003). In the early 1990s, MBR installations were mostly constructed in external configuration. After the mid-1990s, with the development of SMBR system, MBR applications in municipal wastewater extended widely. In the past 15 years, MBR technology has been of increased interest both for municipal and industrial wastewater treatment in North America.

The hesitancy on the part of North American municipalities to consider alternative treatment systems to the well-established conventional treatment options delayed the introduction of MBRs into the municipal arena. Industrial applications, particularly for high-strength, difficult-to-treat waste streams, on the other hand, allowed for the considerations of alternative technologies, such as MBRs (Yang *et al.*, 2006). Nevertheless, currently, commercial application in treating industrial wastewaters does not constitute a high percentage of total full-scale MBR plants.

Zenon occupies the majority of the MBR market in North America. In 2006, the North American installations constituted about 11% of worldwide installations. As in other places, in North America too, although plant capacities of MBR systems for municipal wastewater treatment are becoming larger, most of the plants in operation are medium scale or small scale in terms of capacity. The largest capacity MBR plant in operation is in Traverse City, MI at 26 900 $m^3 d^{-1}$, and the two largest capacity plants under construction are in Johns Creek, GA at 60 000 $m^3 d^{-1}$ and King County, Washington State at 136 000 $m^3 d^{-1}$.

4.16.5.1.4 Decentralized MBR plants: Where and why?

MBR technology can also provide decentralized small-scale wastewater treatment for remote or isolated communities, campsites, tourist hotels, or industries not connected to municipal treatment plants. In small communities, houses are spread out, the population density is low, and hence the use of an on-site system for an individual home or for a cluster of homes could be a cost-effective option. For emerging nations with vast unsewered areas, the population has practically no access to water sanitation, whereby wastewater is directly discharged into water bodies or reused for irrigation without treatment, thus spreading waterborne diseases and causing eutrophication and pollution of water resources. MBR technology could provide a decentralized, robust, and cost-effective treatment for achieving high-quality effluent in such instances. MBRs also offer excellent retrofit capability for expanding or upgrading existing conventional WWTPs.

Even when appropriate infrastructure for large-scale water recycling facility exists, the decentralized option may be preferable in some cases. This is because the cost of large-scale water-recycling applications remains high and often uneconomical due to the need to overhaul the existing water-distribution systems. Large-scale water-recycling applications are, hence, currently somewhat restricted. Furthermore, there is a significant risk of cross-connection associated with the dual-reticulation network, which can seriously dampen public support. While the implementation of the large-scale water recycling is expected to take many years, decentralized water recycling can be applied much more readily. It is expected that MBRs can contribute to a significant increase in decentralized water reclamation and reuse activities.

The discussion now centers on the limitations of traditional onsite treatment systems.

A gradual but permanent reduction in per-capita water use through socially acceptable means is widely recognized by all stakeholders in the water industry as the strategic long-term sustainable solution to address the ongoing water shortage currently experienced by many countries (Tadkaew *et al.*, 2007). Decentralized wastewater management is not a new concept. Tchobanoglous *et al.* (2003) defined it as the collection, treatment, and disposal/reuse of wastewater from individual dwellings, clusters of homes or isolated communities, industries, or institution facilities. Traditional decentralized treatment systems such as septic tanks were, in the past, widely used to treat small quantities of wastewater. Due to the likely toughening of environmental legislation in the near future, many of the currently operating wastewater treatments will no longer be acceptable and there will be a need to increase their efficiency significantly. Stricter regulations are found for especially sensitive areas, drinking-water-abstraction areas, and bathing waters. The problem of meeting existing and forecasted more-stringent new regulations affects especially small communities, hotels, and campsites in relatively remote areas without access to sophisticated WWTPs. A major obstacle of decentralized water recycling remains the lack of a suitable technology that can meet the strict and unique effluent criteria required for small-scale water treatment. Some essential requirements are high and reliable treated effluent quality, robustness, tolerance to variable contaminant loading, small footprint, and ease of operation and maintenance.

We now discuss the advantages of MBRs in decentralized treatment. As discussed in Section 4.16.5.1.2, historically, the largest number of MBR applications was for a capacity of less than 100 $m^3 d^{-1}$. This suggests that the application of MBRs for on-site decentralized system is possible and can offer the most advanced wastewater-treatment options in low-density areas at a cost lower than that of conventional large-scale pipe-and-plant systems. Jefferson *et al.* (2000) argued that small-scale WWTPs constitute a potential growth market for the next millennium and urban sustainability through domestic water recycling is a major identified source for this development. Key advantages of MBRs for decentralized wastewater treatment and reuse are:

- High and reliable treated effluent quality, small footprint, and high tolerance to variable contaminant loading.
- Due to the robustness and modular nature of MBRs, small-scale MBRs can retain the superiority over conventional treatment methods such as septic tanks with regard to effluent quality, which has been very well documented in the literature (Fane and Fane, 2005).
- MBRs can be easily combined with other complementary treatment technologies such as UV disinfection and pre-screening, which can further enhance the robustness of the treatment system and hence make it particularly suitable for water-recycling applications.

The MBRs for decentralized treatment are not without limitations. Besides the obstacles against widespread application of MBR, in general, the high capital cost can be seen as the key limitation of small-scale MBRs although currently there is very little information to substantiate this premise. Friedler and Hadari (2006) analyzed the economic feasibility of on-site graywater-reuse systems in buildings based on MBR systems. They found that on-site MBR systems became feasible when they were used for the treatment of wastewater incorporating several buildings together because cost was sensitive to building size. Therefore, the on-site MBR system for single building might be unfeasible. This could be a limitation of decentralized MBR systems. However, the true cost of water supply, which takes into account the externalities of resource depletion, was not used in their analysis. It is expected that as the demand for decentralized MBRs increases and membrane technology continues to develop, the use of on-site MBRs even for individual dwellings can be cost competitive in the near future.

Some of the examples of worldwide decentralized MBRs are discussed next. The successful introduction of MBR systems into small-scale and decentralized applications has led to the development of packaged treatment solutions from most of the main technology suppliers. Sports stadia, shopping complexes, and office blocks are becoming typical end users, especially in areas of water stress (Stephenson *et al.*, 2000; Melin *et al.*, 2006; Tadkaew *et al.*, 2007).

The application of MBRs in Japan to date has predominantly concerned small-scale installations for domestic wastewater treatment. One of the earliest reported case studies is on graywater recycling facilities in the Mori building, Tokyo (Stephenson *et al.*, 2000). The plant consists of a sidestream Pleiade MBR (Ubis) to treat the building flow of 500 $m^3 d^{-1}$. The selection of an MBR over a traditional treatment process saved an area equivalent to 25 car-parking places. The treated graywater contained less than 5.5 $mg l^{-1}$ BOD and below-detection level of suspended solids, colon bacilli, and *n*-hexane extract, enabling reuse of the graywater. Today, the main Japanese MBR providers such as Kubota or Mitsubishi Rayon offer commercial MBR package plants for on-site domestic water treatment.

In Australia, small-scale MBR systems for graywater recycling at a single household level have been marketed by several companies such as AquaCell in New South Wales and BushWater in Queensland (Tadkaew *et al.*, 2007).

Commercially available systems in Europe include the package treatment plant Clereflo MBR (Conder Products, UK), designed to service populations up to 5000 and the ZeeMOD (Zenon Environmental Inc.) which is available for flow rates

of up to 7500 $m^3 d^{-1}$. Most of the manufacturers offer similar systems which means that effluent qualities of 5:5:5 ($mg l^{-1}$) (BOD: NH4-N:SS) are now routinely available to end users as standard treatment options (Melin *et al.*, 2006). Households/community units (4–50 p.e.) is a concept pioneered by Busse (Germany) in 2000 (Lesjean and Huisjes, 2008). This has become a very competitive market (at least eight products available in Germany). The units are mostly covered by maintenance contracts. The number of sales is expected to increase to address wastewater schemes of small and remote communities, although the revenue may remain marginal in the overall European MBR market.

An example in USA is in eastern San Diego County, California, where expansion of an existing casino and development of a shopping mall required extension to the existing treatment facilities. The existing extended aeration system was converted to a ZeeWeed MBR allowing almost triple the capacity of the infrastructure (Melin *et al.*, 2006). The scheme has been operational since July 2000 with the water quality meeting the California tertiary effluent standards for water-reclamation plants.

4.16.5.2 Commercialized MBR Formats

As mentioned in Section 4.16.3.1, the first-generation MBRs in wastewater treatment used a sidestream format, in which feed was pumped from the bioreactor through an external membrane system. This approach was suitable for the early stage, small-scale applications for difficult-to-treat feeds. An alternative format was developed in the 1990s using modules submerged in the bioreactor tank, or in an adjoining compartment. This was much more cost effective for treating larger-scale flows with more easily treatable wastewater.

The submerged format is available with modules either in a flat-sheet configuration or as hollow fibers or capillary membranes. Originally, the favored concept was to submerge the modules directly into the bioreactor for simplicity. However, in order to gain better control of the balance between the biological and filtration-treatment capacity, it is now more common to use the membrane in an external membrane tank (Brow, 2007). The external arrangement allows the size and design of the membrane tank to be optimized independently, with practical advantages for operation and maintenance.

The sidestream approaches are also divided into two formats – the long-established traditional method of crossflow, now used only for the most difficult feeds, and the newer concept of airlift, which uses air to recirculate the feed and thereby significantly reduces energy demand. Both sidestream formats use tubular membranes.

4.16.5.3 Case-Specific Suitability of Different Formats

The competing MBR formats based on submerged and sidestream configurations each have their own pros and cons for different application types and plant size.

The energy cost for the aeration to control membrane fouling in the MBR is of an order similar to the microbiology aeration for an easy-to-treat feed, and increases by 2.5–3.0 times for the more difficult feed (Cornel and Krause, 2006). Crossflow is more energy intensive – very high cross-flow velocities (up to 5–6 $m^3 h^{-1}$) may be necessary to control the fouling; but for the more difficult feeds, it may be the only option that works reliably. Airlift is a more cost-effective way of improving mass transfer through the creation of slug-flow conditions in the lumen of the membrane tubes (Laborie *et al.*, 1997), but there is a limit to how much air flow can be used while retaining slug-flow conditions. Airlift technology has a power cost similar to that of the submerged technology.

In general, submerged MBR formats based on hollow fibers have been found to provide the most cost-effective solution for large-scale, easy-to-treat applications. Technology has been developed with optimized packing density and aeration bubble size to achieve stable performance at minimum energy use (Fane *et al.*, 2005). However, this format can experience operational difficulties due to fibers becoming matted close to the potted ends, and therefore pretreatment and removal of hairs and fibers is essential. Hollow-fiber technology hence requires more instrumentation and control.

The submerged MBR formats based on flat sheets have been found to be cost effective for similar types of wastewater, but due to higher air use and lower compactness, tend to be selected for small- to medium-scale duties. The flat-sheet format has operational advantages in terms of plugging and cleaning, and has been used in somewhat more difficult feeds.

Flat-sheet systems have the advantage of relatively low manufacturing cost compared to hollow-fiber systems. However, packing density tends to be significantly lower than a hollow-fiber system (e.g., by a factor of 2.5–3 times). Therefore, flat-sheet systems tend to have a cost advantage for small- to medium-scale systems, whereas hollow fiber becomes more attractive at large scale due to the footprint advantage (Pearce, 2008b). The comparison is made more complicated, however, since aeration costs for hollow-fiber systems are often lower. This means that the most cost-effective solution for total treatment costs at medium scale is closely contested, and both approaches are found across the size range due to site-specific circumstances, which could favor either solution.

Lesjean *et al.* (2004), taking into account the current knowledge, anticipated a future market share as follows: for municipal applications, it is expected that the hollow-fiber submerged configuration would be competitive for medium- to large-size plants. For small to medium sizes, flat-sheet technologies would have an advantage. However, in case of larger plants, or a plant refurbishment, the alternative membrane scheme (secondary/tertiary treatment followed by an MF/UF membrane filtration) is very likely to be cost competitive, unless high-cost land has to be purchased for the construction. This multi-barrier scheme will also be easier to control and to optimize because of the disconnection of the treatment steps. It will also be associated with the lowest risk in relation to the membrane operation, as the membranes will be operated under smooth hydrodynamic conditions in terms of particle matter, turbulence, and backwash régime. In a recent paper, Lesjean and Huisjes (2008) reiterated this expectation despite the present trend of large MBR plant construction.

The airlift format has been developed as a low-energy alternative to the energy-intensive cross-flow sidestream format,

which has been used historically for the most difficult feeds. As mentioned earlier, the energy cost of crossflow prohibits it as a treatment option for any application other than small scale or where there is no other treatment option. However, the airlift has very low energy use, and may even undercut the energy requirements of the submerged options, due to the advantage of containment of the feed inside the tubular membrane (Van 'T Oever, 2005; Futselaar *et al.*, 2007). Since airlift eliminates operator contact and has good operational characteristics, it may as well make a major impact on the MBR market in the long run. Pearce (2008a, 2008b) argued that the airlift format may find applications throughout a broader range than the submerged formats. Figure 15 depicts the concept of airlift MBR.

4.16.5.4 MBR Providers

4.16.5.4.1 Market share of the providers

The global market value of MBR is expected to rise up to US$500 million by 2013 from around US$300 million in 2008 (BCC Research, 2008). The MBR market is dominated by three companies, namely GE–Zenon, Kubota, and Mitsubishi Rayon Engineering (MRE). Only GE–Zenon and Kubota have a strong presence in Europe and North America, while MRE have until now mainly focused on sales in Asia. All these companies use submerged formats, with GE–Zenon and MRE

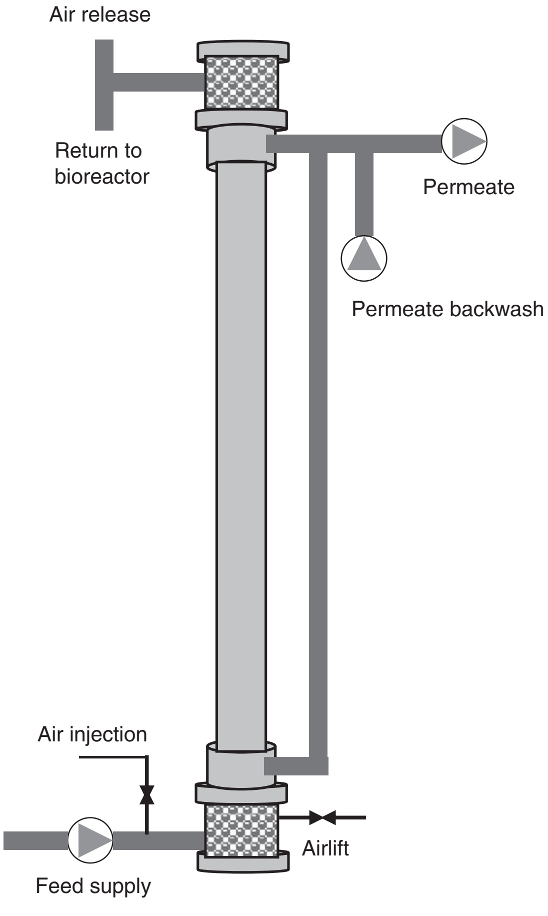


Figure 15 The concept of airlift MBR.

using hollow-fiber membranes, and Kubota, flat-sheet membranes. Another three companies too have an international presence, namely Siemens–Memcor, Norit, and Koch-Puron, but the sales for these three companies makes up a small portion of the worldwide market. Among the latter three, Norit promotes the airlift format. Figure 16(a) shows the worldwide relative market share (in terms of installations numbers) for the three large players (Yang *et al.*, 2006; Pearce, 2008b).

The MBR market has several dozen regional or application specialists, quite a few of who use flat-sheet formats as adopted by Kubota: for example, Japan's Toray and A3 from Germany. In addition to these international companies, there are a further 30 companies in the European Union (EU) market that have either significant regional presence, or an application focus, or a low-level international presence (Lesjean and Huisjes, 2008). Many of these companies are significant in the local markets, but individually, they have a small share of the international market.

It is interesting to note that the MBR market has characteristics different from that of the UF/MF market. In UF/MF, there are 10–12 significant players with worldwide presence, with four market leaders, none of who dominate the market. Besides these companies, other regional players are relatively insignificant (Pearce, 2008a, 2008b).

Zenon is long established in the market and has been one of the major companies promoting the MBR concept, and the use of PVDF membranes. The North American market is dominated by Zenon (Yang *et al.*, 2006) as shown by the revenue share illustrated in Figure 16(b) and has many more opportunities in the municipal sector than in industry. Zenon leads the European market as well (Figure 16(c)).

Kubota was one of the early pioneers of the MBR concept, encouraged by a Japanese Government initiative in the 1980s. They achieved a very large number of installations in small- to medium-scale systems, initially focusing on the residential/commercial market in Japan and have approached export markets through exclusive partnerships. Kubota has a significantly greater number of plants than Zenon, with a slightly higher proportion of industrial plants. Many of Kubota's installations in Japan and Korea are for small-scale municipal and domestic applications. Figure 17 shows the market characteristics of the two market leaders, Kubota and Zenon, illustrating the significantly different market strategies with regard to the size of plant targeted. Kubota is the strongest market player for industrial and small-scale municipal applications.

MRE is a long-established supplier of MBR, with a very strong position in the relatively mature MBR market in Japan and Korea. There are a large number of references for this technology in Asia, but relatively few installations elsewhere. MRE also has a very large number of installations, with a higher proportion of industrial users, mostly with small flowrates.

Koch Membrane Systems (KMS) is a long-established membrane manufacturer and membrane-systems company. In 2004, KMS acquired the MBR start-up company Puron, which had been founded in 2001. They introduced an approach to fiber potting different from that of the other hollow-fiber module providers.

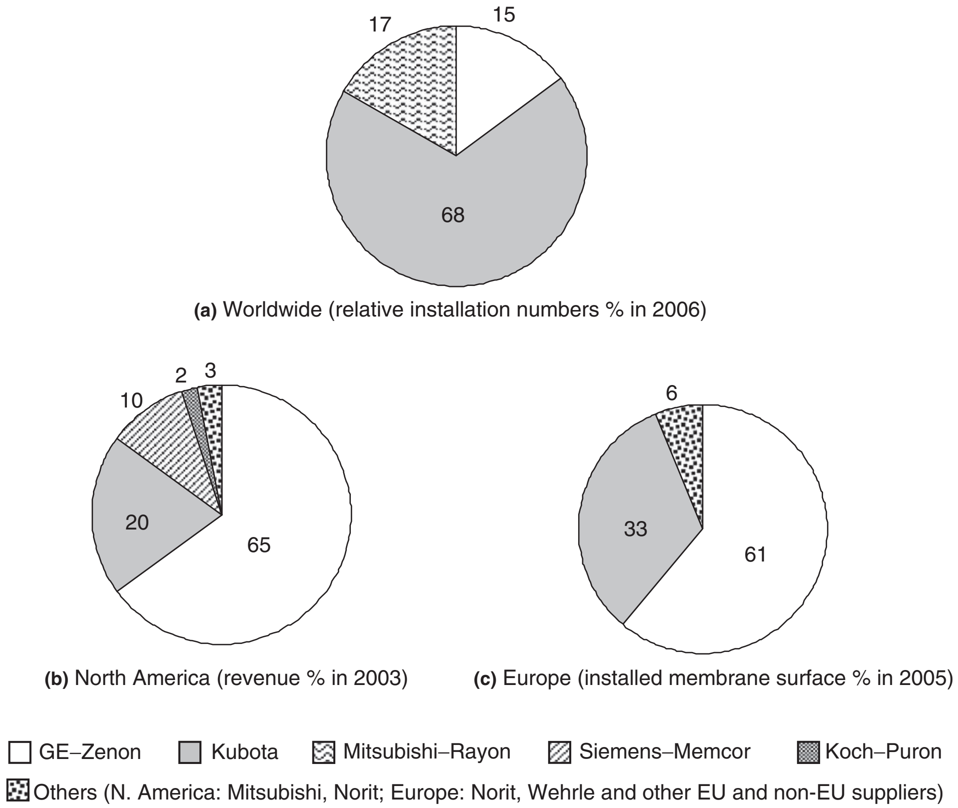


Figure 16 Market share of the suppliers. Data from (a) Yang Q, Chen J, and Zhang F (2006) Membrane fouling control in a submerged membrane; (b) Pearce G (2008 b) Introduction to membranes – MBRs: Manufacturers' comparison: Part 1. *Filtration and Separation* 45(3): 28–31; and (c) calculated from Lesjean B and Huisjes EH (2008) Survey of the European MBR market: Trends and perspectives. *Desalination* 231: 71–81.

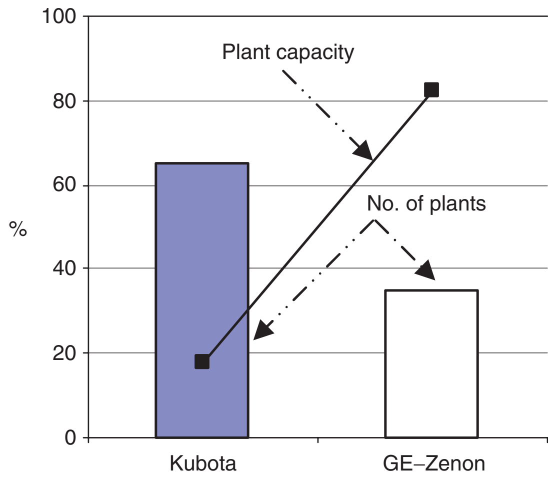


Figure 17 Relative market share (number of plants and capacity) showing distinct market strategies of the two market leaders.

Memcor have extensive experience in the use of their products in wastewater polishing. Their very fine polypropylene (PP) fibers developed in the 1980s were inexpensive and flexible, but unfortunately had low chlorine tolerance (Judd *et al.*, 2004). In the late 1990s, Memcor developed a PVDF fiber, and now use the PVDF fiber for their MBR product range. The Memjet product is characterized by high permeability and packing density, providing a competitive position for capital and operating costs. However, worldwide market share for MemJet MBR is not very significant, since the company tends to focus on selected regional markets (Yang *et al.*, 2006; Pearce, 2008b).

4.16.5.4.2 Design considerations

The design of the reactor (including membrane, baffle, and aerator locations) and the mode of operation of the membrane are key parameters in the optimization of the system. The leading MBR providers propose several MBR designs. In each case, the process proposed is very specific. Not only are the membrane material and configuration used different, but the operating conditions, cleaning protocols, and reactor designs also change from one company to another. For example, the flat-sheet membrane provided by Kubota does not require backwash operation, while hollow-fiber membranes have been especially designed to hydraulically backwash the membrane on a given frequency.

The MBR industry first developed in Japan with the use of chlorinated polyethylene (PE) flat-sheet membrane by Kubota, and PE fibers by MRE (Stephenson *et al.*, 2000). The modified PE is characterized by reasonable strength, flexibility, wettability, and resistance to chlorine. Although PE is normally made as an MF membrane, it has relatively low permeability, so process fluxes of PE membranes tend to be at the

low end of the range. Consequently, PE membranes are very cost effective at small scale, but struggle to compete in larger-scale systems.

In the 1990s, PVDF became established in MBRs through the reinforced capillary fiber in Zenon's ZW 500 module (Yamato *et al.*, 2006). PVDF has impressive performance in terms of strength and flexibility, but is significantly more expensive as a polymer. Nevertheless, PVDF membranes can achieve substantially higher flux, thereby overcoming price disadvantage. Recently, MRE also developed a PVDF-based membrane system. This membrane, designated as SADF, promises to be very competitive in both capital and operating costs, and despite it having a lower packing density than the PE product, it operates at much higher flux. With several companies now offering PVDF products in both capillary and flat-sheet formats, this is the dominant membrane polymer in the MBR market (Pearce, 2008c, 2008d).

The third significantly used membrane polymer in MBR is a reinforced PES, used by Koch–Puron. Although PES is an important polymer in water treatment, in wastewater applications, its lack of flexibility limits the possibility of using air scour. Reinforcing the capillary does allow air scour, but at the expense of permeability. The Puron product uses reinforced PES rather than the PVDF, favored by its rivals. However, its main distinguishing feature is that the membrane fibers are potted at only one end. This overcomes the problem of fouling below the potting interface by hairs and fibers, which is a problem for the other hollow-fiber technologies (Vilim *et al.*, 2009).

Norit is the one major MBR company that offers a system based on a sidestream format with tubular membranes rather than a submerged format. Crossflow is only used for small-scale applications, with feeds that are difficult to treat, whereas airlift is cost effective for larger-scale municipal applications (Futselaar *et al.*, 2007).

Table 9 summarizes the specifications of the membranes used by different suppliers and Figure 18 compares the packing density and applicable flux of the membranes.

Each of the suppliers makes regular improvements in air usage, since this has an important impact on total water cost. For example, the flat-sheet suppliers now use 1.5-m panels, which reduce air flow by up to 30% compared to the original 1 m panel (Pearce, 2008c, 2008d). In addition, they also use double-deck stacks wherever possible, which further improves air-usage efficiency. In addition, the companies using hollow fiber use intermittent aeration, for example, based on a timer in the case of Zenon, or in proportion to flow in the case of Koch–Puron. Memcor introduced a novel cleaning method by using a mixture of air and mixed liquor, instead of using only air bubbles, to scour the membranes. The air bubbles effectively scour the membranes and the semi-crossflow of mixed liquor along the membranes continuously delivers the refresh mixed liquor to the membrane surface, minimizing the solid-concentration polarization at the membrane surface and therefore reducing filtration resistance. These enhancements have significantly reduced air usage and therefore power cost.

4.16.5.4.3 Performance comparison of different providers

Few large-scale studies based on comparison of the commercially available MBR systems have been conducted. The city of San Diego, California, and the research consultant, Montgomery Watson Harza, have been evaluating the MBR process through various projects since 1997, including feasibility of using MBRs to produce reclaimed water (Adham and Gagliardo, 1998, 2000), optimization of MBR operation, and parallel comparison and cost estimations of the four leading MBR suppliers (Adham *et al.*, 2004). MBRs were evaluated for their ability to produce high-quality effluent and to operate with minimum fouling. In terms of hydraulic performances, it

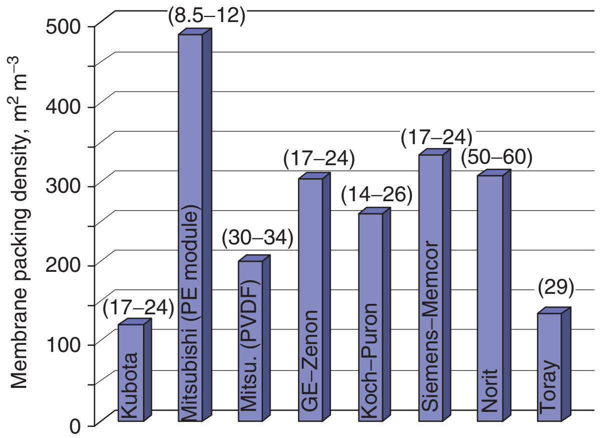


Figure 18 Packing density (bar chart, $m^2\ m^{-3}$) and flux (values within parentheses, $l\ m^{-2}\ h^{-1}$) of membranes from different suppliers.

Table 9 MBR supplier specifications[a]

Company	*Membrane material*	*Pore size, μm*	*Membrane format*	*Fiber/tube dia (id,od),mm*	*pH tolerance*
Kubota	Cl_2 PE	0.4	FS	–	1–13
Mitsubishi	PE	0.4	HF	0.37, 0.54	1–13
Mitsubishi	PVDF	0.4	HF	11, 2.8	1–10
GE–Zenon	PVDF	0.04	HF	0.8, 1.9	2–10.5
Koch–Puron	PES	0.05	HF	–, 2.6	2–12
Siemens–Memcor	PVDF	0.04	HF	–, 1.3	2–10.5
Norit[b]	PVDF	0.03	TUB	–, 5.2 or 8.0	1–11
Toray	PVDF	0.08	FS	–	1–11

[a]All the membranes have moderate hydrophilicity and high chlorine resistance.
[b]All the companies except Norit use submerged format; Norit supplies airlift sidestream MBRs.
FS, flat sheet; HF, hollow fiber; TUB, tubular.

was shown that all four processes were able to cope with flux rates exceeding $33\,l\,m^{-2}\,h^{-1}$ and HRTs as low as 2 h. A 6-year development program has also been initiated for the introduction of MBR technology in the Netherlands market. Started in 2000, a comparative study of four $750\,m^3\,d^{-1}$ MBRs carried out by DHV water has been reported (van der Roest *et al.*, 2002b). Three MBR plants, treating a design flow of $300\,m^3\,d^{-1}$ each, have been operated in parallel during 2003 and 2004 in Singapore (Le-Clech *et al.*, 2006). A 4-year study, started in 2001, comparing the performance of Mitsubishi, Kubota, and Zenon MBR was conducted by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) (Judd, 2006). The Zenon MBR exhibited the most stable performance in the study. Although these studies have been conducted with the MBR systems running in parallel (with the same influent water), the MBR maximum flux, operating conditions and general design applied were those recommended by the suppliers, and therefore somewhat different for each system. This makes it difficult to make a fair comparison. Therefore, it is not possible to classify the MBRs as a function of their relative hydraulic performances, which need to be considered along with the cleaning protocols applied to each system. Mansell *et al.* (2004) performed measurements in which MS2 coliphage were seeded to the influent of a Kubota MBR (characteristic pore size 0.4 μm) and a Zenon MBR (characteristic pore size 0.04 μm). Permeate concentrations showed a log removal range of 3.2–7.4 for the Kubota installation and 5.32–7.5 for the Zenon installation. All of the heavy metals detected in the influent were removed to levels below detection limit, as well as the VOCs that were measured.

4.16.5.5 Standardization of Design and Performance-Evaluation Method

The MBR market is very fragmented and exhibits many MBR filtration products with diverse geometries, module capacities, and operational modes (De Wilde *et al.*, 2008; Lesjean and Huisjes, 2008). Although this situation promotes a competitive market, it is detrimental for the acceptance of the technology as a state-of-the-art process, and raises concern with potential clients or end users. From the point of view of the MBR operators, the possibility of interchanging filtration modules of different companies/suppliers would facilitate the replacement of the modules at the end of their life, and would reduce the risk of a supplier withdrawing from the market or releasing a new series of the product. In addition, the stakeholders in the industry employ various methods of membrane characterization and performance evaluation. This creates confusion among the users and prohibits fair comparison.

Based on an extensive survey of the MBR industry, De Wilde *et al.* (2008) provided an overview of the market interests/expectations and technical potential of going through a standardization process of the SMBR technology in Europe. Due to the predominance of submerged filtration systems in municipal applications, the study focused only on this configuration. Two different aspects of standardization were considered:

- standardization of MBR filtration modules toward interchangeable modules in MBRs and
- standardization of MBR acceptance and monitoring test methods toward uniform quality-assessment methods of MBR filtration systems.

4.16.5.5.1 Standardization of MBR filtration systems

In relation to the market expectations, about 20 potential technological, financial, economical, or environmental benefits/opportunities and drawbacks/threats of MBR module standardization for suppliers and operators were identified and mapped. It appeared that the number of advantages and disadvantages was quite balanced for both sides of the market, the main advantage perceived by the industry being that standardization should contribute to the growth of the MBR market. Other main advantages/opportunities are avoidance of vendor lock-in, price decrease, and increased trust and acceptance. Main disadvantages/threats for the end users are overdimensioning of civil constructions and supplementary works and costs to the peripherals during replacement. Main disadvantages for the module suppliers seem to be the higher competition, lower profit margins, and a limitation for innovative module producers to enter the market.

From the technical point of view, the analysis showed that a standardization process common for both flat-sheet and hollow-fiber membranes/modules would not be realistic. In order to achieve interchangeability of filtration modules, not only should the prospect of pure dimensional standards for the module be considered, but also the design and mode of operation of the peripheral components, such as the filtration tank, pumps, blowers, and pretreatment should be borne in mind. More than 30 technical factors hampering or interfering with a standardization process were identified and quantified, and their relative potential for affecting the possible outcome was evaluated. For instance, four factors were grouped as the extremely high hindering factors: module dimensions, filtration tank dimensions, specific permeate production capacity, and specific coarse-bubble aeration demand. These factors are mainly the result of a completely different geometry and design of the filtration module and discussions for the standardization of MBR filtration systems should in essence focus on these factors. For each category, more or less the same number of obstacles lies ahead. Nevertheless, the nature of some of these obstacles or points of attention can be different. Some factors are specifically important for FS modules (e.g., flushing of air-supply pipes and design of a permeate-collection tank), and others for HF modules (e.g., type of prescreening, whether gravity filtration or any other type).

4.16.5.5.2 Standardization of MBR characterization methods

The survey conducted by De Wilde *et al.* (2008) also revealed the respondents' consensus in general on the positive impact of harmonization of membrane-acceptance tests at module delivery and monitoring methods on municipal MBR market growth. Some important parameters, for which a common definition and measurement protocol could be helpful, are mentioned below:

- clearly defined and harmonized parameters to monitor membrane fouling, integrity, and aging;

- a common definition of membrane lifetime for the guarantee clause;
- determination/definition of flux (operation and nominal design);
- common definition for sustainable peak hydraulic load;
- harmonized tests to check membrane performances over a defined period and under specific conditions;
- characterization method for membrane acceptance at module delivery;
- minimum requirements and technical methods to check membrane performance at plant commissioning;
- monitoring methods of normalized permeability in clear water, permeability in sludge, transmembrane pressure, and fouling rate;
- monitoring methods of sustainable flux and maximum flux; and
- operating conditions (biology and filtration systems) for warranty clauses.

It is interesting to note that, most of the newcomers in the market are developing their systems so that they can easily replace the products of the two main suppliers (Zenon–GE and Kubota). A standardization process driven by the end users could accelerate this evolution and contribute to the market development (Lesjean and Huisjes, 2008). Pearce (2008a, 2008b, 2008c, 2008d) also pointed out that, although the dimensions of the relatively newer Puron products are not identical to Zenon's ZW 500d or MRE's SADF, the elements are similar, and cassettes made from the elements could be used interchangeably. This begins to introduce retrofit possibilities into what hasuntil now been a fragmented market with no standardization.

4.16.6 Future Vision

In addition to the alleviation of the technology bottlenecks illustrated in this chapter, a radical shift from the conventional concept of advanced wastewater treatment is deemed imperative. In the context of sustainable water system, the advanced treatment must couple technologies to produce water of the required quality and realize material conversion from waste as well. The required quality does not always mean high quality. The quality comes from necessity. Membrane technology has the potential to be an on-demand quality provider just by separation. The conversion mainly comes from the biological reaction in the MBR. Three aspects of a sustainable society, namely, the low carbon society, sound material cycle society, and ecological society, are notable. From the point of view of sustainable water system, the advanced wastewater-treatment processes can be classified into the categories of energy saving (or productive), material productive, and ecologically oriented. The MBR technology might match more with the first two. However, present MBR technologies are still large energy consumers. Next-generation MBRs need to be developed to reduce the significant aeration requirement (by compact module design and sludge-concentration control techniques) and recover energy (e.g., by adding other organic wastes and combining anaerobic digestion for methane recovery).

In line with the proposed definition of advanced treatment, the notion needs to be changed from organic wastewater treatment to water/biomass production by developing next-generation MBRs where the membrane acts as a separator of water and biomass and biomass is utilized for energy production. The concept is illustrated in Figures 19 and 20.

4.16.7 Conclusion

MBR is a physicobiological hybrid process. The membrane provides a physical barrier for hygienically safe and clean water with the help of microbial–ecological treatment that can achieve good public acceptance. It is also well recognized by the experts that the clear membrane permeate makes post treatment easy; then, a variety of hybrid systems having the MBR as the core can be considered depending on the specific quality requirements of the reclaimed water . These advantages

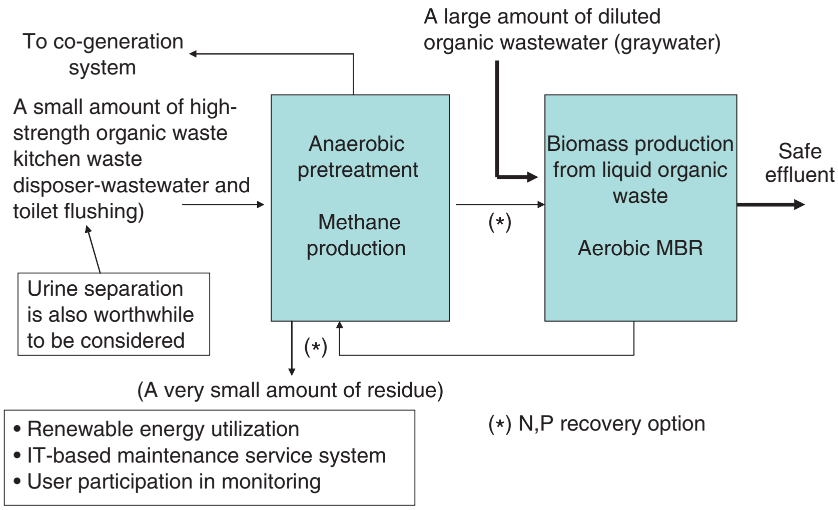
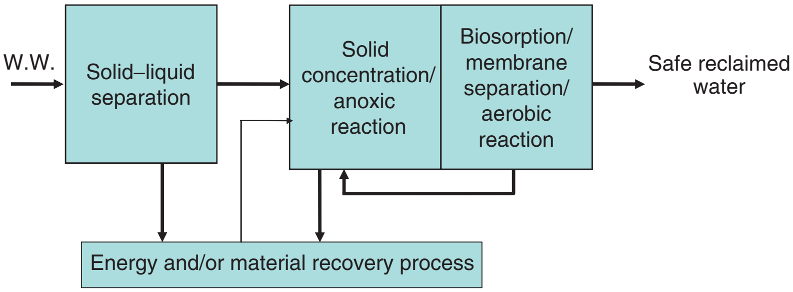


Figure 19 Next-generation MBR system: anaerobic combination for on-site small-scale advanced treatment.



Other than biogas production, physicochemical treatments are also candidates for energy recovery, for example, supercritical water gasification of sludge–water mixture where the biomass sludge is utilized as energy source to produce hydrogen from water molecules (coupling clean energy production).

Figure 20 Next-generation MBR system: renovation of existing wastewater-treatment plants.

make MBR a good device in water reclamation and/or advanced wastewater treatment. The continued push toward stricter discharge standards, increased requirement for water reuse, and greater than before urbanization and land limitations fuel the use of MBRs. However, there is room for improvement to utilize the potential of the MBR fully. The challenges will center on energy saving, ease of operation, simplified membrane cleaning and replacement strategies, and peak-flow management. The international adventure on R&D of MBR technologies continues.

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