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Membrane Separation Bioreactors for Wastewater Treatment

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ABSTRACT: With continuing depletion of fresh water resources, focus has shifted more toward water recovery, rense, and recycling, which require an extension of conventional wastewater treatment technologies. Downstream external factors like stricter compliance requirements for wastewater discharge, rising treatment costs, and spatial constraints necessitate renewed investigation of alternative technologies. Coupled with biological treatment processes, membrane technology has gained considerable attention due to its wide range of applicability and the performance characteristics of membrane systems that have been established by various investigations and innovations during the last decade. This article summarizes research efforts and presents a review of the how and why of their development and applications. The focus is on appraising and comparing technologies on the basis of their relative merits and demerits. Additional facts and figures, especially regarding process parameters and effluent quality, are used to evaluate primary findings on these technologies. Key factors such as loading rates, retention time, cross-flow velocities, membrane types, membrane fouling, and backwasbing, etc. are some of the aspects covered. Membrane applications in various aerobic and anaerobic schemes are discussed at length. However, the emphasis is on the use of membranes as a solid/liquid separator, a key in achieving desired effluent quality. Further, technology development directions and possibilities are also explored. The review concludes with an economic assessment of the technologies because one of the key technology selection criteria is financial viability.

KEY WORDS: membrane bioreactor, membrane technology, solid/liquid separation, membrane air diffusers, membrane fouling, backwashing, micro-porous membranes.

I. INTRODUCTION

The use of biological treatment can be traced back to the late nineteenth century. By the 1930s, it was a standard method of wastewater treatment (Rittmann, 1987). Since then, both aerobic and anaerobic biological treatment methods have been commonly used to treat domestic and industrial wastewater. During the course of these processes, organic matter, mainly in soluble form, is converted into

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H_2O, CO_2, NH_4^+, CH_4, NO_2^-, NO_3^- and biological cells. The end products differ depending on the presence or absence of oxygen. Nevertheless, biological cells are always an end product, although their quantity varies depending on whether it is an aerobic or anaerobic process. After removal of the soluble biodegradable matter in the biological process, any biomass formed must be separated from the liquid stream to produce the required effluent quality. A secondary settling tank is used for the solid/liquid separation and this clarification is often the limiting factor in effluent quality (Benefield and Randall, 1980).

In recent years, effluent standards have become more stringent in an effort to preserve existing water resources. Recycling and reuse of wastewater for secondary purposes is on the rise due to dwindling natural resources, increasing water consumption, and the capacity limitations of existing water and wastewater conveyance systems. In both cases, achieving a high level of treatment efficiency is imperative.

The quality of the final effluent from conventional biological treatment systems is highly dependent on the hydrodynamic conditions in the sedimentation tank and the settling characteristics of the sludge. Consequently, large volume sedimentation tanks offering several hours of residence time are required to obtain adequate solid/liquid separation (Fane et al., 1978). At the same time, close control of the biological treatment unit is necessary to avoid conditions that lead to poor settleability and/or bulking of sludge. Very often, however, economic constraints limit such options. Even with such controls, further treatment such as filtration, carbon adsorption, etc. are needed for most applications of wastewater reuse. Therefore, a solid/liquid separation method different from conventional methods is necessary.

Application of membrane separation (micro- or ultrafiltration) techniques for biosolid separation can overcome the disadvantages of the sedimentation tank and biological treatment steps. The membrane offers a complete barrier to suspended solids and yields higher quality effluent. Although the concept of an activated sludge process coupled with ultrafiltration was commercialized in the late 1960s by Dorr-Oliver (Smith et al., 1969), the application has only recently started to attract serious attention (Figure 1), and there has been considerable development and application of membrane processes in combination with biological treatment over the last 10 years.

This emerging technology, known as a membrane bioreactor (MBR), offers several advantages over the conventional processes currently available. These include excellent quality of treated water, which can be reused for industrial processes or for many secondary household purposes, small footprint size of the treatment plant, and reduced sludge production and better process reliability.

The purpose of this monograph is to provide a comprehensive review of membrane bioreactor technology. The application of membranes in different stages of biological treatment processes, the historical development of membrane bioreators,

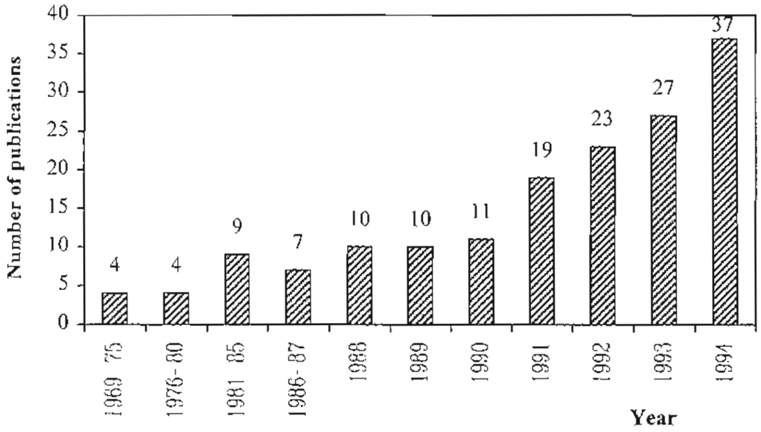

FIGURE 1. Number of studies published on MBR.

and factors affecting the design and performance of MBR processes are discussed. A number of case studies for each type of major MBR application along with some cost information on MBR processes is also presented.

II. FEATURES OF MEMBRANE APPLICATION IN BIOLOGICAL WASTEWATER TREATMENT

As our understanding of membrane technology grows, they are being applied to a wider range of industrial applications and are used in many new ways for wastewater treatment. Membrane applications for wastewater treatment can be grouped into three major categories (Figure 2): (1) biosolid separation, (2) biomass aeration, and (3) extraction of selected pollutants. Biosolid separation is, however, the most widely studied and has found full-scale applications in many countries (Table 1). Use of combined night-soil treatment and wastewater reclamation at plant scale operations in buildings in Japan are examples of some successful applications, and in these cases membrane-coupled technology is considered a standard process (Yamamoto and Urase, 1997). Solid/liquid separation bioreactors employ micro- or ultrafiltration modules for the retention of biomass for this purpose. The membranes can be placed in the external circuit of the bioreactor or they can be submerged directly into the bioreactor (Figure 2a).

Asymmetric membranes consist of a very dense top layer or skin with a thickness of 0.1 to 0.5 μm, supported by a thicker sublayer. The skin can be placed either on the outside or inside of the membrane, and this layer eventually defines the characterization of membrane separation.

TABLE 1
Commercial Scale Solid/liquid Separation MBR Plants

Company	Commercial name	Country	Type of Waste	Number of Plants	Capacity (m^3/d)	Ref.
Rhone Poulenc-TechSep	UBIS	France	Domestic	>40	<400	Roullet, 1989
Dorr Oliver	MSTS	USA	Domestic	1	13.6	Smith et al., 1969
Thetfort Syst	Cycle-LET	USA	Domestic	>30	<200	Irwin, 1990
Kubota	Kubota	Japan	Domestic	8	10–110	Ishida et al., 1993
	Kubota	UK	Domestic	1	96	Brindle and Stephenson, 1997
Mitsui Petrochemical Industries	ASMEX	Japan	Human excreta	>40	—	Lambert, 1983
Zenon Env Inc.	Zenogem	Canada	Industrial	1	116	Knoblock et al., 1994
Dorr Oliver	MARS	USA	Industrial	1	38	Li et al., 1984
Membratek	ADUF	RSA	Industrial	2	80/500	Ross and Strohwald, 1994
SITA/lyonnaise des Eaux	—	France	Landfill leachate	3	10–50	Trouve et al., 1994a
Membratek	—	S.Africa	Industrial	2	100–500	Brindle and Stephenson, 1997
Grantmij	—	Germany	Landfill leachate	3	10–50	Brindle and Stephenson, 1997
Degrement	—	France	Industrial	1	500	Brindle and Stephenson, 1997

A submerged membrane should be outer-skinned. In general, permeate is extracted by suction or, less commonly, by pressurizing the bioreactor. In the external circuit, the membrane can be either outer- or inner-skinned, and the permeate is extracted by circulating the mixed liquor at high pressure along the membrane surface. In the later case, the concentrated mixed liquor at the feed side is recycled back to the aeration tank.

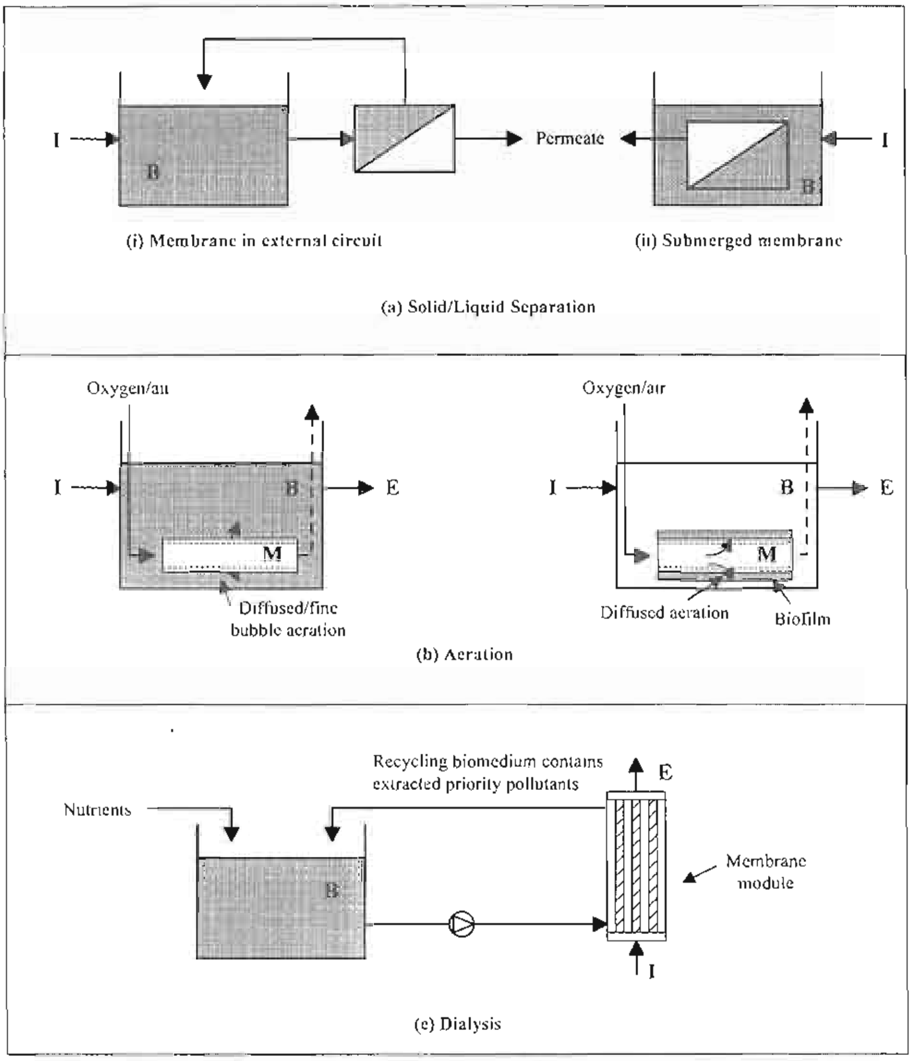

FIGURE 2. Features of membrane application in biological wastewater treatment. (B, bioreactor; M, membrane module; I, influent; E, effluent.) (Adapted from Brindle and Application in Wastewater Treatment.)

Gas-permeable porous membranes can be used to aerate the mixed liquor in the aeration tank by bubbleless oxygen mass transfer (Yasuda and Lamaze, 1972). At the same time, they can be used for fine bubble aeration (Semmens, 1989; Matsuoka et al., 1992). In certain cases, 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 phases into the biofilm in the other direction (Brindle and Stephenson, 1996). Because the membranes can form bubble-free or fine-bubble mass transfer, the efficiency is very high.

Conventional membrane modules can be used in either a flow-through or dead-end mode as presented in Figure 2b. In the flow-through mode, the air or oxygen is continuously pumped through the hollow fibers and gas is vented to keep the partial pressure of oxygen high along the membrane. In the dead-end mode, the membrane is pressurized with air or oxygen by sealing one end of the fibers or by sending the gas from both ends. Most studies reported to date have focussed on the flow-through mode, and researchers argue that the dead-end mode should be avoided because it significantly reduces performance and may result in water vapor condensation inside the membrane fibers. However, because air or oxygen is vented out in the flow-through system, part of the pumped gas is wasted, and thus the gas transfer efficiency is reduced. In addition, volatile organic compounds (VOCs) can diffuse across the membrane into the air stream (Semmens, 1989), VOCs in wastewater can be very effectively stripped and vented off to the atmosphere. Both these problems can be overcome in the dead-end mode. Also, as the total amount of air/oxygen supplied should diffuse through the membrane module, the efficiency is improved and VOCs stripped off can be minimized if not completely reduced.

An extractive membrane bioreactor was developed to extract (by dialysis) toxic organic pollutants present in industrial wastewater to a bio-medium for subsequent degradation (Livingston, 1994). In dialysis mode, organisms can be maintained in an optimal growth environment through nutrient supplementation while at the same time digesting inhibitory or recalcitrant compounds that diffuse across the membrane. Mass transfer of the pollutants across the membrane is driven by a concentration gradient, because the bio-medium passing on the membrane walls acts as a sink. Although these three applications are described separately, they are not mutually exclusive, and they may be coupled together to achieve added advantages for each process (Brindle and Stephenson, 1997). For example, a study by the authors to use hollow fiber membrane for solid/liquid separation and aeration in alternate cycles indicates such coupling (Parameshwaran et al., 1998).

III. DEVELOPMENT OF MEMBRANE BIOREACTORS

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 reverse osmosis. Many combinations of membrane solid/liquid separators in biological treatment processes have been studied since. The trends that led to the development of today's MBR are depicted in Figure 3. When the need for wastewater reuse first arose, the conventional approach was to use advanced treatment processes (Figure 3a). For irrigation, this treatment may be limited to filtration and disinfection, whereas for building reuse or ground water recharge it may also include reverse osmosis (RO). For example, Water Factory 21 in Orange Country (California, USA) uses a treatment process that consists of lime softening, air stripping, recarbonation, sand filtration, carbon adsorption, and RO for biologically treated effluent (Mills, 1996). The treated water is used to recharge the ground water. This scheme is relatively complex and produces large amounts of chemical sludge.

The progress of membrane manufacturing technology and its applications could lead to the eventual replacement of tertiary treatment steps by microfiltration or ultrafiltration and this simplified method is being evaluated at Water Factory 21 in the U.S. Parallel to this development, microfiltration or ultrafiltration was used for solid/liquid separation in the biological treatment process and the sedimenta-

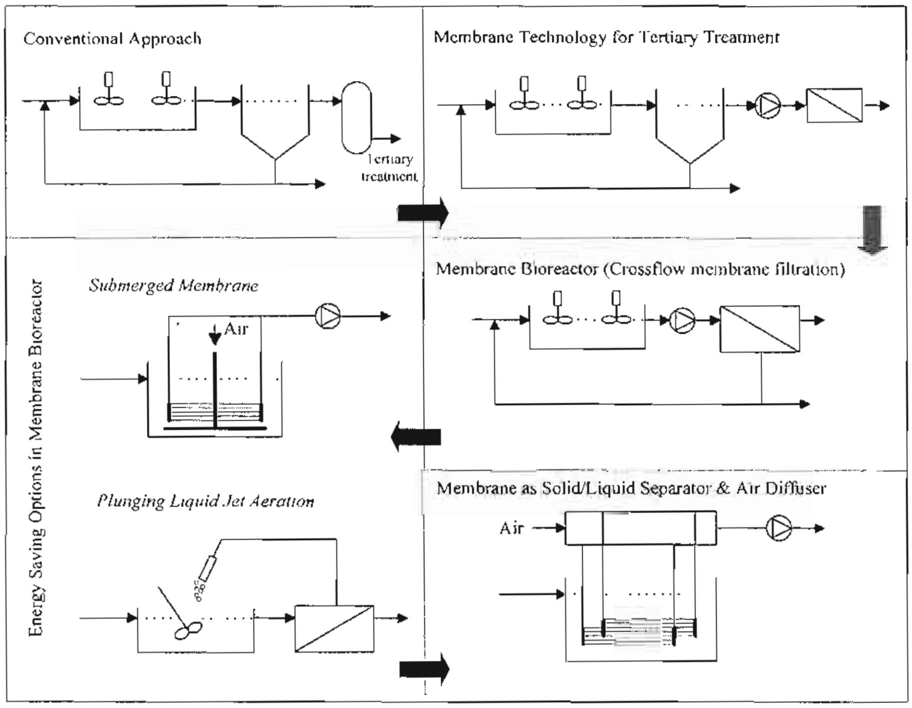

FIGURE 3. Trends in MBR development.

tion step could also be eliminated. 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., 1977; Krauth and Staab, 1988; Muller et al., 1995). However, higher energy costs to maintain the crossflow velocity led to the next stage of development — submerging the membranes in the reactor itself and withdrawing the treated water through membranes (Yamamoto et al., 1989; Kayawake et al., 1991; Chiemchaisiri et al., 1993; Visvanathan et al., 1997). In this development, membranes were suspended in the reactor above the air diffusers. The diffusers provided the oxygen necessary for treatment to take place and scour the surface of the membrane to remove deposited solids. In a parallel attempt to save energy in membrane coupled bioreactors, the use of jet aeration in the bioreactor has been investigated (Yamagiwa et al., 1991). The main feature is that the membrane module is incorporated into the liquid recirculation line for the formation of the liquid jet such that aeration and filtration can be accomplished with only one 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. The limited amount of oxygen transfer possible with this technique restricts this process to small-scale applications. However, using only one pump makes it mechanically simpler and therefore useful to small communities. The invention of air back-washing techniques for membrane declogging led to the development of using the membrane itself as both clarifier and air diffuser (Parameshwaran et al., 1998). In this approach, two sets of membrane modules are submerged in the aeration tank. While the permeate is extracted through one set, 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.

A. Advantages of MBR

There are many advantages in using a MBR process, the prime ones being the treated water quality, the small footprint of the plant, and less sludge production and flexibility of operation.

1. Treated Water Quality

The major problem of conventional activated sludge processes is the settling of sludge. This is caused by poor flocculation of microfloras or the proliferation of filamentous bacteria. Because solids and colloids are totally eliminated through membrane separation, settlement has no effect on the quality of treated water. Consequently, the system is easy to operate and maintain. This is important with industrial wastewater, because a lack of nutrients leads to excessive growth of filamentous organisms resulting in poor settlement. Because the final effluent does not contain suspended matter, this enables the direct discharge of the final effluent into the surface water and the reuse of effluent for cooling, toilet flushing, lawn watering, or, with further polishing, as process water.

2. Flexibility in Operation

In a MBR, sludge retention time (SRT) can be controlled completely independently from hydraulic retention time (HRT). Therefore, a very long SRT can be maintained resulting in the complete retention of slow-growing microorganisms such as nitrifying or methanogenic bacteria and this results in greater flexibility of operation.

3. Compact Plant Size

Volumetric capacities are typically bigh because a high sludge concentration can be maintained independently of settling qualities. HRTs as low as 2 h have been satisfactorily applied (Chaize and Huyard, 1991), and fluctuations on volumetric loading have no effect on the treated water quality (Chiemchaisri et al., 1993). For example, sludge concentrations between 25 and 30 kg/m^3 have been achieved regularly as opposed to the more common 4 to 6 kg/m^3 in the conventional aerobic process (Yamamoto and Win, 1991). Moreover, the higher turbulence maintained within the mixed liquor to prevent the membrane from fouling also prevents the flocculation of biosolids and keeps them highly dispersed. An analysis on the floc size distribution of MBR sludge and conventional activated sludge indicates that the floc size in the MBR (a number of samples from different MBR plants were analyzed) are very much smaller than 100 μm and concentrated within a small range. On the other hand, floc size from conventional activated sludge processes varied from 0.5 to 1000 μm (Zhang et al., 1997). The smaller flocs from MBRs could stimulate a higher oxygen and/or carbon substrate mass transfer and thus higher activity levels in the system. Zhang and co-workers (1997) also found that nitrification activities in MBR processes averaged 2.28 g NH_4–N/kg MLSS.h, which was greater than in conventional processes (0.95 g NH_4–N/kg MLSS.h). Also, there is an enormous saving in space with MBRs because there is no need for secondary settling devices and post-treatment to achieve reusable quality.

4. High Rate Decomposition

Treatment efficiency is also improved by preventing leakage of undecomposed polymer substances. If these polymer substances are biodegradable, they can be broken down with a reduction in the accumulation of substances within the treatment process. On the other hand, dissolved organic substances with low molecular weights, which cannot be eliminated by membrane separation alone, can be broken down and gasified by microorganisms or converted into polymers as constituents of bacterial cells, thereby raising the quality of the treated water. For example, the permeate from microfiltration of screened raw sewage (feed average BOD_5 = 230 mg/l) had an average BOD_5 of 93 mg/l. This was mainly the soluble portion of the influent BOD_5, although it showed 99% removal of suspended solids and 5.8 log removal of fecal coliforms (Johnson et al., 1996). In contrast, most MBR studies indicate the effluent BOD_5 is below 5 mg/l (Parameshwaran and Visvanathan, 1998; Buisson et al., 1997; Trouve et al., 1994). Due to the high biomass concentration and the fact that bio-oxidation is an exothermic process, temperature increase can be maintained at the maximum activity temperature level. Maximum growth rates are about five times higher than the activity commonly observed in activated sludge systems. Based on cubic meter of reactor volume, combining high activity with high biomass concentration results in conversion rates 10 to 15 times higher than conventional conversion rates (Buisson et al., 1997), an especially useful feature in cold climates.

5. Low Rate Sludge Production

Studies on MBR indicate that the sludge production rate is very low (Table 2). Chaize and Huyard (1991) have shown that for treatment of domestic wastewater, sludge production is greatly reduced if the age is between 50 and 100 days. Low F/M ratio and longer sludge age in the reactor is generally used to explain this low production rate.

Praderie (1996) demonstrated that the viscosity of sludge increases with age, eventually limiting the oxygen transfer in the MBR system. Therefore, he recommends limiting the MLSS concentrate to 15 to 20 g/l for effective oxygen transfer. It was also noted that with increased age there was greater difficulty in sludge dewaterability, which could be attributed to excess amount of cellular polymer formation (Parameshwaran, 1997; Erikson et al., 1992).

It is also anticipated that micrological activity can be modified with increased sludge age, but little published information is available on the subject. The initial microscopic observation (Praderier, 1996; Pliankarn, 1996) on microorganism population indicates that with increased sludge age, reduction in filamentous bacteria increased rotifers and nematodes.

6. Disinfection and Odor Control

In this membrane filtration process, the removal of bacteria and viruses can be achieved without any chemical addition (Pouet et al., 1994; Langlais et al., 1992; Kolega et al., 1991). Because all the process equipment can be tightly closed, no odor dispersion occurs. Comparison of conventional biological processes and MBR is shown in Table 3 and depicts the advantages discussed above.

TABLE 2
Comparison of Sludge Production in Conventional Activated Sludge Process (ASP) and MBR Process Treating Domestic Wastewater

Type of Process	SRT (d)	Sludge production	Ref.
ASP	10–20	0.7–1 kg MLSS/kg BOD5	Hsu and Wilson, 1992
ASP	14	0.7 kg MLSS/kg BOD5	E.I.A, 1994
ASP	33	0.6 kg MLSS/kg BOD5	E.I.A, 1994
MBR	25	0.53 kg MLVSS/kg BOD5	Trouvé et al., 1994a
MBR	25	0.26 kg SS/kg BOD5	Trouvé et al., 1994b
MBR	≈50	0.22 kg MLSS/kg BOD5	Takeuchi et al., 1990

With the exception of wastewater reuse, membrane separation activated sludge processes have not been widely used. Obstacles to more widespread use include:

- High capital and operating costs
- Current regulatory standards can be achieved by conventional treatment process
- Limited experience in use of membranes in these application areas
- Lack of interest by the membrane manufacturers

Membranes will only find greater application in the wastewater industry if they can achieve the required regulatory standards or better at the same or less cost

TABLE 3
Comparison of Operating Data for Conventional, Extended Aeration ASP, and AS/UF Treatment Processes

		Processes		
Parameters	Unit	ASP/UF	Conventional ASP	Extended aeration ASP
System reactor volume	1	2,663	3,423	13,694
Influent BOD	mg/l	250	250	250
System MLSS	mg/l	10,000	2,500	3,500
Organic loading rate	kg BOD/kg. MLSS.d	0.12	0.20–0.70	0.10–0.15
Volumetric loading rate	kg BOD /m³.d	1.35	0.59	0.27
Reactor dissolved oxygen	mg/l	1.50	1.50	1.50
Sludge retention time	d	Infinite	2–0	11
Re-circulation ratio	%	240	25	50–100
Hydraulic retention time	h	5	6	12–24

From Smith et al., 1969.

compared with present processes, or if regulations were to tighten further such that conventional processes can no longer achieve the desired effluent quality.

IV. FACTORS AFFECTING THE MBR PROCESS PERFORMANCE

The main aim of memhrane-coupled bioreactors is to improve the efficiency of the biological process step such that high-quality effluent is obtained. Because biological treatment and membrane separation are rather distinct processes, the combined MBR process is relatively complex. To optimize the MBR process, many parameters have to be considered. These include solid concentrations, sludge age, and the hydraulic retention time (HRT) in the biological step as well as the flux rate, material costs, and the energy cost of the membrane separation. The treatment and disposal of the waste sludge also needs to be considered. Comparisons made on the waste sludge properties of the conventional activated sludge process and the MBR process indicates that dewatering of MBR waste sludge is difficult compared with the conventional process. This has been attributed to higher organic matter content and excess production of extracellular polymers (Parameshwaran, 1997). As all these parameters are interrelated, optimizatiou is complicated. For example, an increase in sludge concentration can enhance the biological stage. However, when sludge concentration exceeds a certain limit, the permeation flux rapidly declines due to a dramatic rise in the viscosity of the sludge mixture (Praderie, 1996). An increase in sludge concentration can also affect the gas transfer efficiency, and the energy requirements for the aeration therefore increase will (Praderie, 1996).

Permeation flux of membrane filtration is affected by the raw materials of the membrane and its pore size as well as operational conditions such as the pressure driving force, the liquid velocity/turbulence, and the physical properties of the mixed liquor being filtered (Tables 4 to 6).

A. Type of Membrane

Selection of the membrane module plays an important role on the membrane flux achieved. Membranes can be categorized according to the materials used (organic or ceramic), membrane type (microfiltration or ultrafiltration), module type (plate and frame or tubular or hollow fiber), filtration surface (inner skin or outer skin), as well as the module status (static or dynamic membranes). All are being tested and many combinations have been considered. There are, however, overlaps and omissions in the combinations considered largely due to poor communication among international researchers.

The flux will vary depending on the combination considered. For example, submerged hollow fiber membrane modules (external skin) show the lowest flux of 3.5 $l/m^2.h$, while ceramic microfilters show the highest of 100 $l/m^2.h$ (Tables 4 to 6). Smooth surface membranes (ceramic) offer more resistance to cake layer

TABLE 4
Characteristics and Operating Conditions of Aerobic MBR Process (Membrane in External Circuit)

Wastewater type	Domestic					Synthetic			
Membrane configuration	UF (plate and frame)	MF (hollow fiber)	UF (plate and frame)	MF (hollow fiber)	MF/UF (tubular)	MF/UF	MF (hollow fiber)	UF (spiral wound)	UF (tubular)
Membrane material	Noncelluiose organic	Polyvinyl acetate	Polysulfone/ cellulose	Ceramic	Polysulfone/ acrylic	—	Polyester	Polysul-fone/	Polysul-fone/
Pore size (Dalton/μm)	—	—	50,000	0.1	0.1/50,000/ 800,000	200,000	—	50,000	0.01
Filtration area (m^2)	—	266	0.42	1.1	—	0.00385	0.1	—	0.1
Cross flow velocity (m/s)		—	1.5	—	1–5	—	2.2–3.6	0.5	4.5
Transmembrane pressure (kPa)	152–186	—	100–200	100	150–400	20–80	200–250	100	135–260
Temperature (°C)	—	—	20	29	20	20	30	25	27
MLSS[a] (kg/m^3)	15	—	8–10	3.7 ± 0.8	5–40	—	—	4–12	6–40
Flux ($L/m^2.h$)	—	25	10–90[b]	80–100	—	4.8–11.4	20	29.2	45
Frequency of cleaning	—	1/h	—	—	—	—		1/month	—
Reference	Smith et al., 1969 1969	Audic, 1986	Chaize and Huyard, 1991	Trouve et al., 1994c	Muller et al.,1995	Suwa et al., 1992	Bailey 1994	Ishiguro, 1993	Lübbecke et al., 1995

Wastewater type	Industrial		Sour vegetable canning		Ice cream
Membrane configuration	UF hollow fiber	UF plate and frame	UF Tubular	UF Tubular	Tubular
Membrane material	Organic	Polysulfone	Polysulfone	Polysulfone	Ceramic
Pore size (Dalton/μm)	—	—	0.04	0.01	0.2
Filtration area (m^2)	2	2.17	0.22	0.55–1.1	0.06
Cross flow velocity (m/s)	—	2	2.53	—	—
Transmembrane pressure (kPa)	140	190–390	275	250	10
Temperature (°C)	30	30–38	31.5	—	25
MLSS[a] (kg/m^3)	7.5–12.4	20–28	11	47	—
Flux ($l/m^2.h$)	50	23–70	66	40	24
Frequency of cleaning	—	1/h	—	—	—
Reference	Hare et al., 1990	Sato and Ishi, 1991	Krauth and Staab, 1993	Lübbecke et al., 1995	Scott and Smith, 1997

[a] Mixed-liquor suspended solids.
[b] Unit ($l/m^2.h.bar$).

TABLE 5
Characteristics and Operating Conditions of Aerobic MBR Process (Submerged Membrane)

Wastewater type	Synthetic		Domestic	Industrial	Synthetic	Synthetic	Industrial	Domestic
Membrane configuration	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber	MF Hollow fiber
Membrane material	Polyethylene	Polyethylene	Polyethylene	Polyethylene	Polyethylene	Polyethylene	Polyethylene	Polyethylene
Pore size (μm)	0.1	0.1	0.1–0.2	0.1	0.1	0.1	0.1	0.2
Filtration area (m^2)	0.9	0.3	4–10	0.27	0.6	0.6	0.3	1
Transmembrane pressure (kPa)	40	13	8	27	80	40	20–80	20/44/96
Temperature (°C)	23-24	16–22	16.6	25–30	5	25	—	29-31
MLSSa (kg/m^3)	10–11	7–16	8.3	10.9–18.2	4	2.5	4.5	12–14
Flux (l/m^2.h)	9	6	5.5	6.7–3.5	8.33	12.5	18	6/14/27
Frequency of cleaning								
Reference	Yamamoto et al., 1989		Takeuchi et al., 1990	Yamamoto et al., 1991	Chiemchaisri, et al., 1992, 1993	Chiemchaisri et al., 1992, 1993	Benitez et al., 1995	Parameshwaran et al., 1998

TABLE 6
Characteristics and Operating Conditions of Anaerobic MBR Process

Wastewater type	Brewery			Wheat starch	Pulp and paper	High strength SS Distillery	Synthetic	Industrial	High strength		
Membrane configuration	MF plate and frame	UF (tubular)	UF	MF (hollow fiber/tubular)	MF (P and F)	MF	UF (P and F)	UF (tubular)	MF	UF	UF
Membrane material	Organic	Polyethersulfone	—	—	—	—	Polysulfone	PVDF	—	—	—
Pore size (Dalton/μm)	0.45	40,000	10,000	0.1	2×10^6	2×10^6	3×10^6	0.1	2×10^6	20,000	10,000
Filtration area (m^2)	0.012	0.44	·	54	20	12	0.02	—	—	0.22	—
Cross flow velocity (m/s)	2	1.5	—	0.9	1.0	—	0.8	1.5–2	—	—	—
Transmembrane pressura (kPa)	150	160	—	50	40	—	49	100	—	—	—
Temperature (°C)	—	35–40	—	37	35	—	35	37	—	—	—
MLSS[a] (kg/m^3)	15.8	30	31–38	16.9	15	37.5–113.3	15[b]	—	7.6	—	—
Flux (l/m^2.h)	30	28	—	16.25	12.5	—	—	35–45	—	—	—
Frequency of cleaning	—	—	—	25s/6–7 min.	1/2–3 weeks	—	—	—	—	—	—
Reference	Anderson, 1984	Strohwald and Ross, 1992	Fakhru'l-Razi, 1994	Kimura, 1991	Kimura, 1991	Nagano et al., 1992	Harada et al., 1994	Seyfrid and Broockmann, 1995	Miami et al., 1991	Kitamura, 1994	Hall et al., 1995

[a] Mixed-liquor suspended solids.
[b] Mixed-liquor volatile suspended solids, MLVSS.