A review of membrane bioreactors and their potential application in the treatment of agricultural wastewater

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Cicek, N. 2003. **A review of membrane bioreactors and their potential application in the treatment of agricultural wastewater.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **45**: 6.37-6.49. Membrane Bioreactors (MBRs) can be broadly defined as systems integrating biological degradation of waste products with membrane filtration. They have proven quite effective in removing organic and inorganic contaminants as well as biological entities from wastewater. Advantages of the MBR include good control of biological activity, high quality effluent free of bacteria and pathogens, smaller plant size, and higher organic loading rates. Current applications include water recycling in buildings, wastewater treatment for small communities, industrial wastewater treatment, and landfill leachate treatment. This paper summarizes the potential applications of the MBR technology for the treatment of wastewater from agricultural sources. Anaerobic digestion coupled with an aerobic/anoxic membrane bioreactor could be utilized for treating manure and wastewater from livestock operations to levels suitable for direct reuse or safe discharge to surface water bodies. Wastewater generated from industries such as slaughterhouses, meat, dairy, egg, and potato processing and liquor production could potentially be treated with MBRs resulting in compact systems producing high quality reusable water. Also effective removal of nitrates, herbicides, pesticides, and endocrine disrupting compounds may be achieved by MBRs. **Keywords:** membrane filtration, wastewater, manure, food processing, endocrine disruptors.

Les bioréacteurs à membrane (BRM) peuvent être décrits comme étant des systèmes qui combinent des processus de dégradation biologique et de filtration par membrane. Ils ont été utilisés efficacement dans l'enlèvement de contaminants de nature organiques, inorganiques et biologiques présents dans les eaux usées. Les BRM ont comme avantage d'assurer un bon contrôle de l'activité biologique, de produire un effluent de haute qualité débarrassé de bactéries et pathogènes, d'être adaptés aux petites usines ainsi que de pouvoir traiter des eaux usées fortement chargées en matières organiques. Les utilisations courantes incluent le recyclage de l'eau dans des bâtiments, le traitement des eaux usées pour les petites communautés, le traitement industriel des eaux usées de même que le traitement des eaux de lixiviat des dépotoirs. Cet article traite des utilisations potentielles de la technologie des BRM pour le traitment des eaux usées d'origine agricole. La digestion anaérobique combinée à un bioréacteur à membrane aérobique/anoxique pourrait être utilisée pour le traitement du lisier et des eaux usées des fermes d'élevage rendant ainsi l'effluent réutilisable ou acceptable pour une décharge directe dans les cours d'eau. Les eaux usées produites par les industries de transformation de la viande, du lait, des œufs et des pommes de terre, les abattoirs et les usines de production d'alcool pourraient potentiellement être traitées avec des systèmes BRM compacts produisant une eau de haute qualité et réutilisable. De plus les BRM peuvent enlever les nitrates, herbicides, pesticides ainsi que les composés affectant l'activité endocrine. **Mots clés**: membrane filtrante, eaux usées, lisier, transformation alimentaire, inhibiteur endocrinien

INTRODUCTION

The demand for clean water is vast, whether it be for human consumption, agricultural application, or industrial use. Problems in Walkerton, Ontario (O'Connor 2002) and North Battleford, Saskatchewan, (Laing 2003) as well as numerous boil water advisories issued across Canada (Perchard 2001) have brought water quality and wastewater treatment to the forefront of public consciousness. Canadians desire not only water that is low in organic or mineral contaminants, but also free of biological entities such as bacteria, pathogens, and viruses. Therefore, treatment processes that are reliable, cost-efficient, and effective in removing a wide range of pollutants are required. One very promising technology involves the utilization of membrane bioreactors (MBRs).

MBRs can be broadly defined as systems integrating biological degradation of waste products with membrane filtration (Cicek et al. 1998b). They have proven quite effective in removing both organic and inorganic contaminants as well as biological entities from wastewater. Advantages of the MBR include better control of biological activity, effluent that is free of bacteria and pathogens, smaller plant size, and higher organic loading rates (Cicek et al. 1998a). Not only have there been numerous successful pilot scale studies, some full scale units are in use in various parts of the world. Current applications include water recycling in buildings (Kimura 1991; Yokomizo 1994), municipal wastewater treatment for small communities (Buisson et al. 1998; Cote et al. 1997; Fan et al. 1996; Irwin 1990; Trouve et al. 1994), industrial wastewater treatment (Berube and Hall 2001; Dufresne et al. 1998; Fan et al. 1998, 2000; Hogetsu et al. 1992; Knoblock et al. 1994; Krauth and Staab 1993; Minami 1994; Scholzy and Fuchs 2000; Sutton et al. 1983), and landfill leachate treatment (Manem 1996; Wehrle 1997, 1998).

Several promising areas of MBR application remain unexplored and require detailed experimental evaluation. These could include treatment of wastes generated from agricultural sources and livestock operations, wastewater originating from food processing industries, removal of herbicides, pesticides, and endocrine disrupting substances from wastewater and water streams, and biological nitrate removal (Fonseca et al. 2000; Mansell and Schroeder 1998; Nah et al. 2000; Urbain 1996). New configurations of bioreactors which would be multifunctional and be integrated into various treatment sequences need to be developed to expand the applicability of such systems. This paper introduces the MBR technology, summarizes the types and configurations of current MBR applications, and discusses its potential utilization in a number of areas related to agricultural wastewater treatment.

BACKGROUND

The membrane bioreactor technology

Biological treatment technologies have been utilized in wastewater reclamation for over a century. Out of the many different processes employed, the activated sludge system has proven to be the most popular (Tchobanoglous et al. 2003). The implementation of membranes within the treatment sequence of a water pollution control facility was initially limited to tertiary treatment and polishing. Ultra-filtration, micro-filtration, or reverse osmosis units were utilized in areas where discharge requirement were very stringent or direct reuse of the effluent was desired (Tchobanoglous et al. 2003). High capital and operational costs as well as inadequate knowledge on membrane application in waste treatment were predominant factors in limiting the domain of this technology. However, with the emergence of less expensive and more effective membrane modules and the implementation of ever-tightening water discharge standards, membrane systems regained interest.

Membrane modules have evolved from being utilized solely in tertiary wastewater treatment to being integrated into secondary wastewater treatment. These systems are now most commonly referred to as membrane bioreactors (MBRs). Figure 1 summarizes the evolution of membrane use in wastewater treatment and demonstrates the basic differences in the treatment trails.

There are several advantages associated with the MBR which make it a valuable alternative over other treatment techniques. First of all, the retention of all suspended matter and most soluble compounds within the bioreactor leads to excellent effluent quality capable of meeting stringent discharge requirements and opening the door to direct water reuse (Chiemchaisri et al. 1992). 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 (Cicek et al. 1998a). Since suspended solids are not lost in the clarification step, total separation and control of the solid retention time (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 species (nitrifying bacteria, bacteria capable of degrading complex compounds) to develop and persist in the system even under short SRTs (Cicek et al. 2001).

The membrane not only retains all 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. 1999c). 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 solid retention times without having 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 making it desirable for water recycling applications. 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. 1999b).

The disadvantages associated with the MBR are mainly cost related. High capital costs due to expensive membrane units and high energy costs due to the need for a pressure gradient have characterized the system. Concentration polarization and other membrane fouling problems can lead to frequent cleaning of the membranes, which stop operation and require clean water and chemicals. Another drawback can be problematic waste-activated-sludge disposal. Since the MBR retains all suspended solids and most soluble organic matter, waste-activated-sludge may exhibit poor filterability and settleability properties (Cicek et al. 1999c). Additionally, when operated at high SRTs, inorganic compounds accumulating in the bioreactor can reach concentration levels that can be harmful to the microbial population or membrane structure (Cicek et al. 1999a).

System configurations

Membrane bioreactors are composed of two primary parts, the biological unit responsible for the biodegradation of the waste compounds and the membrane module for the physical separation of the treated water from mixed liquor. MBR systems can be classified into two major groups according to their configuration. The first group, commonly known as the integrated MBR, involves outer skin membranes that are internal to the bioreactor (Fig. 2). The driving force across the membrane is achieved by pressurizing the bioreactor or creating negative pressure on the permeate side (Buisson et al. 1998; Cote et al. 1997; Rosenberger et al. 2002). Cleaning of the membrane is achieved through frequent permeate back-pulsing and occasional chemical backwashing. A diffuser is usually placed directly beneath the membrane module to facilitate scouring of the filtration surface. Aeration and mixing are also achieved by the same unit. Anoxic or anaerobic compartments can be incorporated to enable simultaneous biological nutrient removal (Cote et al. 1998).

The second configuration is the recirculated (external) MBR, which involves the recirculation of the mixed liquor through a membrane module that is outside the bioreactor. Both inner-skin and outer-skin membranes can be used in this application. The driving force is the pressure created by high cross-flow velocity along the membrane surface (Cicek et al. 1998b; Urbain et al. 1998). A schematic of the recirculated MBR is presented in Fig. 3. The emergence of less expensive and more resilient polymeric membranes along with lower pressure requirements and higher permeate fluxes have accelerated the worldwide commercial use of submerged MBRs (Adham et al. 2001).

Several types and configurations of membranes have been used for MBR applications (Visvanathan et al. 2000). These include tubular, plate and frame, rotary disk, hollow fiber, organic (polyethylene, polyethersulfone, polysulfone,

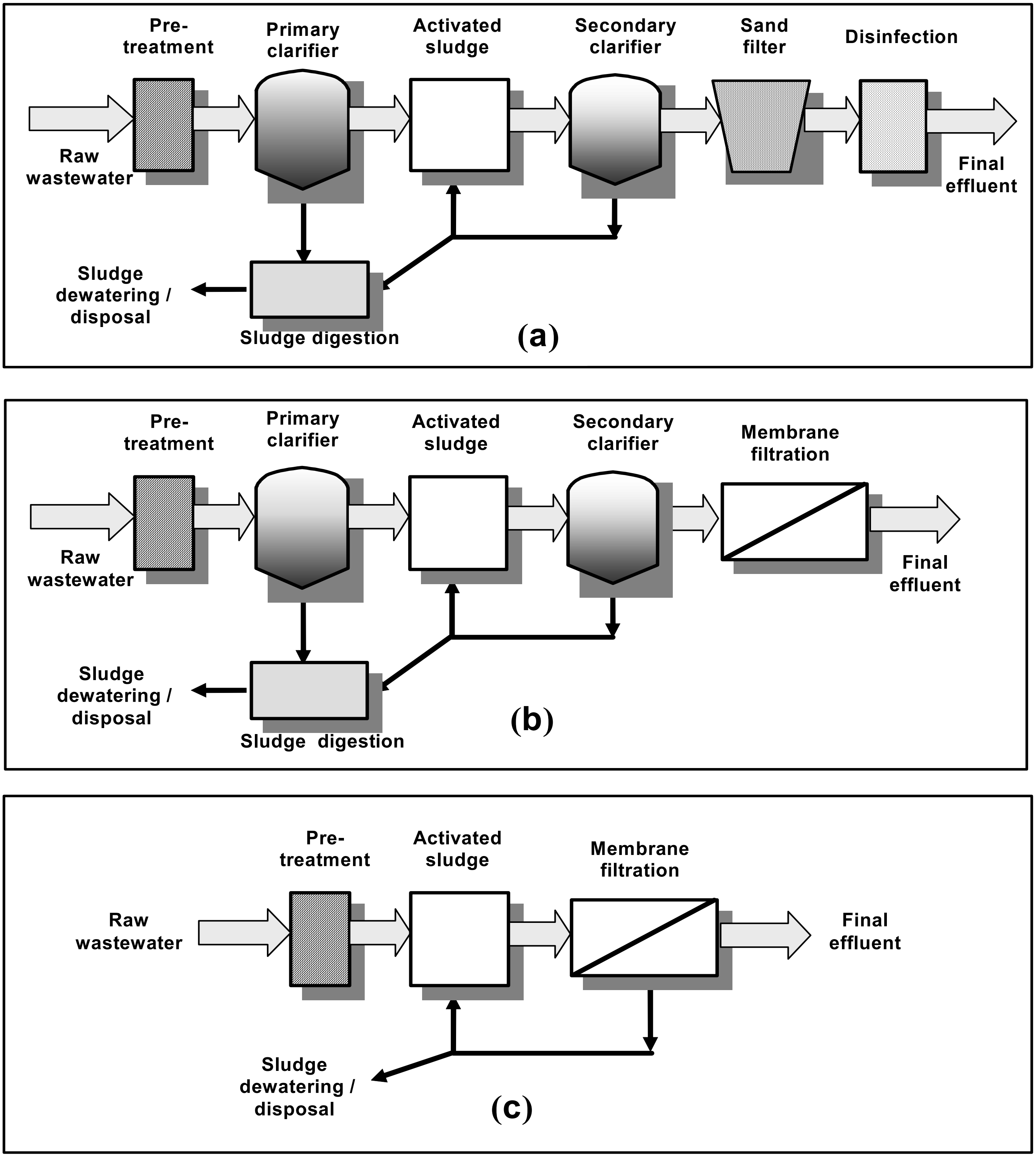

Fig. 1. Flowcharts for (a) conventional wastewater treatment; (b) conventional treatment including tertiary membrane filtration; and (c) membrane bioreactors.

polyolefin, etc.), metallic, and inorganic (ceramic) micro-filtration and ultra-filtration membranes. The pore size of membranes used ranged from 0.01 to 0.4 µm. The fluxes obtained ranged from 0.05 to 10 m/d ($m^3 m^{-2} d^{-1}$), strongly depending on the configuration and membrane material. Typical values for inner skin membranes are reported as 0.5-2.0 m/d and for outer skin membranes as 0.2-0.6 m/d at 20 ºC. The applied trans-membrane pressure ranges from 20 to 500 kPa for inner skin membranes and from -10 to -80 kPa for outer skin membranes (Manem 1996).The membrane used in MBR

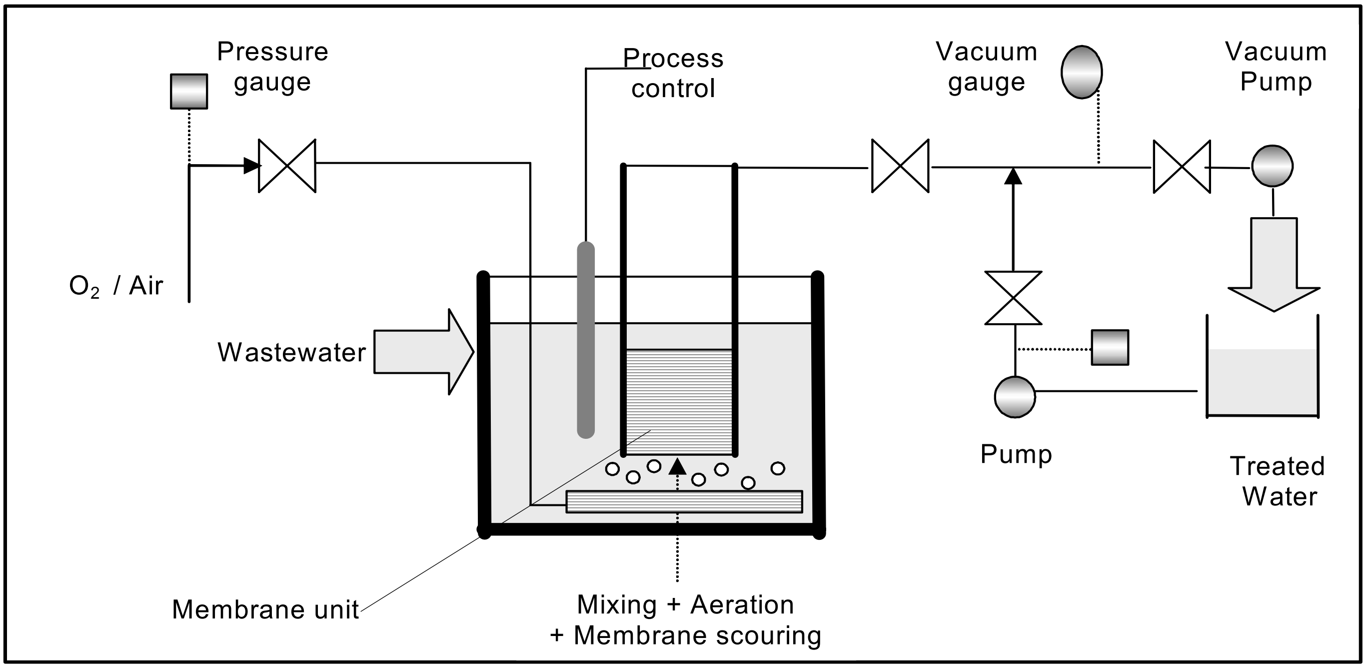

Fig. 2. Schematic of integrated (submerged) MBR.

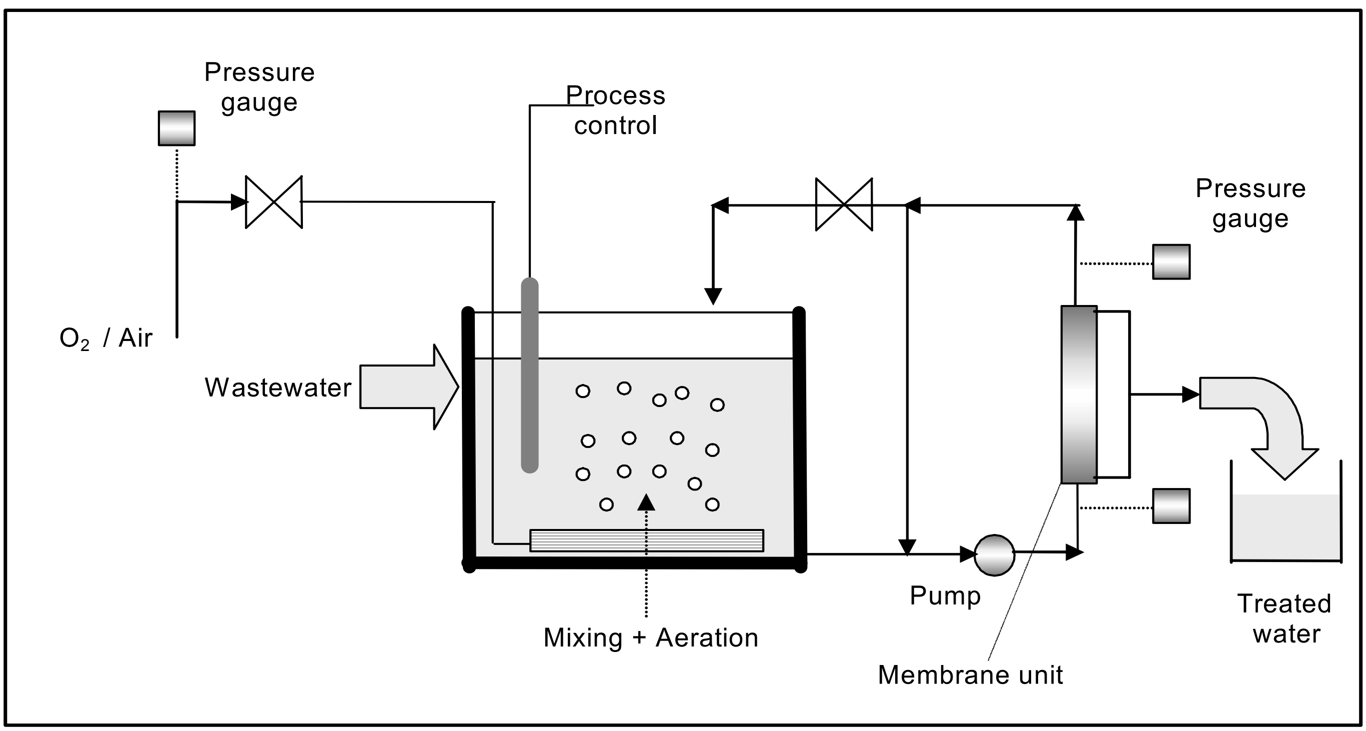

Fig. 3. Schematic of recirculated (external) MBR.

systems must satisfy various criteria. For a review on the selection of membrane material and configuration and on the impact of various operating parameters, a number of research articles and books can be accessed (Brindle and Stephenson 1996; Manem 1996; Stephenson et al. 2000; Van de Roest et al. 2002; Visvanathan et al. 2000).

Applications in municipal wastewater treatment

MBR systems were initially used for municipal wastewater treatment, primarily in the area of water reuse and recycling. Compactness, production of reusable water, and trouble-free operation made the MBR an ideal process for recycling municipal wastewater in water and space limited environments.

Table 1. MBR applications in the area of domestic and municipal wastewater treatment.

Membrane type	Configuration	Size of operation	Treatment success	Country of application	Reference
Ceramic Ulftrafiltration	Plate and frame external	Full-scale Average ~ 125 m^3/d	Effluent COD < 5 mg/L	Japan	Manem 1996
Polymeric Ultrafiltration	Hollow fiber submerged	Pilot-scale < 1.5 m^3/d	Effluent COD < 10 mg/L	Japan	Chiemchaisri et al. 1993
Polymeric Ultrafiltration	Tubular external	Pilot-scale 360-840 m^3/d	Effluent TC < 12 mg/L	The Netherlands	Muller et al. 1995
Ceramic Ulftrafiltration	Tubular external	Pilot-scale 2.4-4.8 m^3/d	COD removal > 94%	France	Fan et al. 1996
Ceramic Ulftrafiltration	Tubular external	Bench-scale 0.16 m^3/d	COD removal > 98%	USA	Cicek et al. 1998a
Polymeric Ultrafiltration	Hollow fiber submerged	Pilot-scale 2.6-5.0 m^3/d	COD removal > 96.5%	Canada/France	Cote et al. 1998
Polymeric Ultrafiltration	Cartridge-disc external	Pilot-scale 48 m^3/d	Effluent COD < 5 mg/L	Korea	Ahn et al. 1999
Polymeric Microfiltration	Hollow fiber submerged	Pilot-scale 1.4-3.8 m^3/d	Effluent BOD_5 < 3 mg/L	USA	Adham and Trussell 2001
Polymeric Ultrafiltration	Hollow fiber submerged	Pilot-scale 6-9 m^3/d	COD removal > 95%	Germany	Rosenberger et al. 2002
Polymeric Ultrafiltration	Hollow fiber submerged	Pilot-scale 46-74 m^3/d	COD removal > 93%	The Netherlands	Van de Roest 2002
Polymeric Ultrafiltration	Plate and frame submerged	Pilot-scale 48-72 m^3/d	COD removal > 91%	The Netherlands	Van de Roest 2002
Polymeric Ultrafiltration	Hollow fiber submerged	Full-scale 750 m^3/d	Effluent BOD_5 < 1 mg/L	USA	Garcia and Kanj 2002
Polymeric Ultrafiltration	Hollow fiber submerged	Full-scale 9000 m^3/d	COD removal > 95%	USA	Lorenz et al. 2002

Legislation in several parts of Japan, encouraging water reuse in large buildings, stimulated the development and application of alternative technologies (Kimura 1991). By the mid 1990s, the development of less expensive submerged membranes made MBRs a real alternative for high flow, large scale municipal wastewater applications. Over 1,000 MBRs are currently in operation around the world with approximately 66% in Japan, and the remainder largely in Europe and North America. Out of these installations, about 55% use submerged membranes while the rest have external membrane modules (Van de Roest et al. 2002). Table 1 summarizes MBR applications in municipal wastewater treatment with respect to type and configuration of the membrane, size of operation (bench, pilot, or full-scale), treatment success, country of application, and their respective reference.

Applications in industrial wastewater treatment

High organic loadings and very specific and difficult to treat compounds are two major characteristics of industrial waste streams that render alternative treatment techniques such as the MBR desirable. Since, traditionally wastewater with high COD content was treated under anaerobic conditions, initial attempts of MBR applications for industrial wastewater were in the field of anaerobic treatment. Table 2 and Table 3 present overviews of MBR applications in the industrial wastewater treatment area. Table 3 focuses on food industry wastewater alone.

Applications in fields of landfill leachate, sludge digestion, and human excrement

In addition to municipal and industrial wastewater treatment, MBRs have been utilized in a number of other areas. One such area is the treatment of landfill leachates. Landfill leachates usually contain high concentrations of organic and inorganic compounds. Conventionally, the treatment of leachates involves a physical, biological, or membrane filtration process (or a combination of them). MBR systems have been successfully utilized with an additional treatment step for inorganics and heavy metal removal, such as reverse osmosis (RO). Several industrial scale plants, combining a MBR and a reverse osmosis system, are presently operated (Manem 1996; Wehrle 1997, 1998).

Table 2. MBR applications in industrial wastewater treatment other than the food industry.

Source wastewater Operation type	Membrane configuration	Size of operation	Treatment success	Country of application	Reference
Wool scouring Anaerobic	Ultrafiltration external	Pilot-scale ~ 10 m^3/d	TOD removal > 89%	Japan	Hogetsu et al. 1992
Various sources Aerobic	Ultrafiltration external	Pilot-scale 0.2-24.6 m^3/d	COD removal > 97%	Germany	Krauth and Staab 1993
Pulp mill Anaerobic	Ultrafiltration external	Pilot-scale ~ 10 m^3/d	TOC removal > 85%	Japan	Minami 1994
Automotive industry (paint line) Aerobic	Ultrafiltration external	Full-scale 113 m^3/d	COD removal > 94%	USA	Knoblock et al. 1994
Metal transforming Aerobic	Ultrafiltration external	Pilot-scale 0.2 m^3/d	COD removal > 90%	Canada	Zaloum et al. 1994
Tannery wastewater Aerobic	Ultrafiltration external	Full-scale 500-600 m^3/d	COD removal > 93%	Germany	Wehrle 1994b
Cosmetic industry Aerobic	Ultrafiltration external	Full-scale	COD removal > 98%	France	Manem 1996
Pulp and paper Aerobic	Microfiltration external	Bench-scale 0.05-0.09 m^3/d	COD removal 68-82%	Canada	Dufresne et al. 1998
Electrical components Aerobic	Ultrafiltration external	Full-scale 10 m^3/d	COD removal > 97%	Germany	Wehrle 1999
Fuel and lubricants Aerobic	Ultrafiltration external	Bench-scale 0.02-0.04 m^3/d	TOC removal > 95%	Austria	Scholzy and Fuchs 2000
Kraft pulp mill Anerobic	Ultrafiltration external	Bench-scale 0.003 m^3/d	TOC removal > 93%	Canada	Berube and Hall 2001

The MBR system was also used in the treatment of human excreta in domestic wastewater. These applications, also known as night soil treatment systems, were typified by the high strength of the waste and the need for on-site treatment. The MBR system replaced a rather complex set of treatment systems which incorporated denitrification, coagulation, filtration, and activated carbon treatment (Magara and Itoh 1991; Manem 1996). Another application of the MBR is in the area of sludge treatment. Conventionally, sludge stabilization in wastewater treatment plants is achieved by a single pass, anaerobic digester. Since the HRT and the SRT are identical in these systems, the capacity is limited and long solid retention times are required for effective solids destruction. Pillay et al. (1994) showed that a microfiltration unit enhances the performance of the digester by decoupling the HRT and the SRT and, thereby, allowing higher volumetric throughput. Table 4 summarizes MBR applications in these three areas in categories of the source of wastewater, type, and configuration of the membrane, size of operation (bench, pilot, or full-scale), treatment success, country of application, and respective reference.

POTENTIAL APPLICATIONS IN AGRICULTURAL WASTE TREATMENT

A self-sustaining waste treatment system for intensive livestock operations

Canada's livestock industry is experiencing rapid growth with an increasing number of large-scale confinement livestock operations. In Manitoba, the hog population has doubled in the past five years (ARDI 2000) and Ontario has over 3.4 million hogs with an increasing number of large-scale, intensive farms (Miller 2000). The growing concern is the environmental impact of waste generated in these facilities in the form of manure, wastewater, unpleasant odors, ammonia, and methane. New large scale farming facilities require large crop areas for nutrient application and in some regions nutrients in livestock waste exceed available cropland capacity to receive them in agronomic rates (Miller 2000). The public is becoming increasingly concerned with the livestock industries potential impact on water and air quality, which will ultimately increase pressure for stricter government regulations.

Intensive livestock operations commonly combine solid and liquid waste in a manure slurry form and have extensive ventilation systems for heat, moisture, and air quality control. If a completely self-sustaining system is desired, the technology selected would have to effectively ameliorate both waste streams, produce reusable water, eliminate unpleasant odors, and be easily upgradeable. A submerged aerobic membrane bioreactor may be used as the centerpiece of such a treatment process complimented by an anaerobic digester or anaerobic lagoon as a pre-treatment step. Since one third of the organics and the majority of nutrients and metals remain in the effluent of anaerobic digesters, a submerged MBR system that facilitates nutrient and organics removal may be utilized. Nitrogen is usually the key nutrient in livestock waste management and a

Table 3. MBR applications in the treatment of food industry wastewater.

Source wastewater Operation type	Membrane configuration	Size of operation	Treatment success	Country of application	Reference
Dairy whey Anaerobic	Ultrafiltration external	Pilot-scale 0.46 m^3/d	COD removal > 94%	USA	Sutton et al. 1983
Maize/egg processing Anaerobic	Ultrafiltration external	Full-scale 500 m^3/d	COD removal > 97%	South Africa	Ross et al. 1992
Brewery effluent Anaerobic	Ultrafiltration external	Pilot-scale ~ 10 m^3/d	TOC removal > 97%	South Africa	Strohwald and Ross 1992
Liquor production Anaerobic	Ultrafiltration external	Pilot-scale ~ 1.25 m^3/d	COD removal > 98%	Japan	Nagano et al. 1992
Rendering plant Aerobic	Ultrafiltration external	Full-scale 102 m^3/d	COD removal > 95%	Germany	Wehrle 1994a
Food ingredients Aerobic	Microfiltration submerged	Full-scale 600 m^3/d	Effluent TSS < 9 mg/L	USA	Cantor et al. 1999
Dairy products Aerobic	Ultrafiltration external	Full-scale 2000 m^3/d	COD removal > 98%	Ireland	Wehrle 2000
Fermentation Aerobic	Ultrafiltration external	Bench-scale ~ 0.01 m^3/d	TOD removal > 94%	Japan	Lu et al. 2000

Table 4. MBR applications in the treatment of landfill leachate, sludge, and human excrement.

Source wastewater Operation type	Membrane configuration	Size of operation	Treatment success	Country of application	Reference
Landfill leachate Aerobic	Ultrafiltration external	Full-scale 50 m^3/d	not available	France	Manem 1996
Landfill leachate Aerobic	Ultrafiltration external	Full-scale 264 m^3/d	COD removal > 80%	Germany	Wehrle 1997
Landfill leachate Aerobic	Ultrafiltration external	Full-scale 250 m^3/d	COD removal > 90%	Germany	Wehrle 1998
Human excrement Aerobic	Ultrafiltration external	Pilot-scale	BOD removal > 99%	Japan	Magara and Itoh 1991
Human excrement Aerobic	Ultrafiltration external	Full-scale	BOD removal > 99%	France	Manem 1996
Sludge digestion Anaerobic	Microfiltration external	Pilot-scale 0.13 m^3/d	not available	South Africa	Pillay et al. 1994

treatment process incorporating nitrification and denitrification is essential. Either intermittent aeration or an anoxic department within the bioreactor can be employed for total nitrogen removal (Cheng and Liu 2001). Metal salts can also be added to reduce phosphorus content in the final effluent. MBRs are capable of producing effluent free of suspended solids, bacteria, and pathogens allowing direct reuse of the product water in the livestock facility. Water reuse in parts of the Canadian Prairies with limited high quality water (e.g. Alberta, Saskatchewan), could stimulate development in the livestock production industry. This would also relieve expansion pressures currently focused in areas of abundant fresh water (e.g. Manitoba).

Aerobic activated sludge reactors have been used on a limited scale as bio-scrubbers for the treatment of odorous air (Bowker 2000). Despite numerous positive reports from full-scale applications in North America, little data are available on the actual performance of these systems with wide ranging concerns on reduction of settling efficiency due to changes in filamentous organisms and bacterial flocs (Burgess et al. 2001). These concerns are alleviated in MBRs where gravitational settling of the microbial solution is replaced by physical filtration. Also, the diffusion and bioconversion of odorous gases are a function of contact time, bubble size, and reactor configuration (Burgess et al. 2001). Submerged MBRs incorporate the membrane unit within the bioreactor and rely on gas and liquid scouring to clean the membrane surface. Since modern livestock operations are equipped with blowers and ventilation systems, booster fans could be added to increase outflow pressure. This concept was explored in past research efforts when biofilter beds (compost and wood chips) were tested for odour removal (Mann et al. 2002). The outlet gas stream could be introduced into an aerobic submerged MBR which would facilitate aeration, agitation, and membrane scouring while significantly reducing the release of odorous gases.

The ultimate goal would be to design a process that would reduce the dependency of intensive livestock producers on crop land, remove unpleasant odours from intensive livestock operations, reuse water on-site, and thereby substantially reduce water use and reduce potential environmental risks associated to the incorrect storage, handling, and application of manure.

Food processing wastewater

The food industry in Canada is the second largest contributor of economic activity and employment. From an environmental perspective, the majority of food processing facilities are characterized by very high water consumption and high organic strength wastewater generation (Parsons 2001). Major waterborne pollutant loadings are biological/chemical oxygen demand, total suspended solids, fats-oils-greases, and nutrients. Most facilities employ on-site primary treatment prior to sending their wastewater to municipal wastewater treatment plants. Large volumes of high strength wastewater both increase the cost of disposal for food processing facilities and present difficult challenges for the municipal wastewater treatment plant operators.

Since MBRs are capable of treating high strength wastewater, attempts were made to evaluate their effectiveness with food processing effluents. Table 3 presents information on these applications in terms of wastewater type, system characteristics, size, and treatment success. As shown in Table 3 all but one application utilized various configurations of external membrane units. At the times of these applications, external membranes were thought to be more suitable for high temperature, high organic strength, and difficult to filter waste streams. High pressure requirements and capital investment costs resulted in the lack of large scale implementation of many such systems. Only Cantor et al.(1999) investigated submerged hollow fiber microfiltration units which proved quite effective and led to the installation of a full-scale internal MBR system which was capable of treating 600 m^3/d of process wastewater.

The emergence of submerged MBRs that utilize fairly economical polymer-based membranes and require less energy than external MBRs has revolutionized municipal wastewater treatment and has tremendous potential in larger scale, high volume throughput facilities across the globe. The potential of reusing the MBR product water on-site for washing or transport purposes offers many cost benefits such as reduced fresh water requirements, lower sewer costs, and possibility for direct discharge to surface waters.

Depending on the wastewater characteristics and effluent requirements, both aerobic and anaerobic submerged MBRs could be employed. Industries such as slaughterhouses, fermentation plants, meat, dairy, egg, and potato processing facilities, and liquor production plants could utilize this technology. Pilot-scale testing and optimization of the process would be required on a case by case basis. The fouling and flux behavior of submerged membranes when exposed to specific waste streams would require detailed evaluation. However, intrinsic characteristics of the MBR technology such as the ability to treat high strength, greatly fluctuating wastewater, resilience in the face of shock loads and toxic chemicals, and production of superior quality effluent would justify consideration of the process in food processing facilities.

Endocrine disrupting substances (EDS), pesticides, and herbicides

The most recent study by the U.S. Geological Survey has identified 95 organic water contaminants in 139 streams across 30 states in the USA (Kolpin et al. 2002). Among the most frequently detected compounds were steroids, hormones, synthetic detergents, and insecticides, which all possess endocrine (hormone) disruptive qualities. The Canadian Environmental Protection Act in 1999 (Department of Justice of Canada 1999) defined a hormone disrupting substance as "a substance having the ability to disrupt the synthesis, secretion, transport, binding, action or elimination of hormones in an organism, or its progeny, that is responsible for the maintenance of homeostasis, reproduction, development, and behavior of an organism." These substances range from natural estrogens such as 17-B-estradiaol, synthetic estrogens such as ethynylestradiol (active compound in birth control pills), industrial chemicals such as alkylphenol etoxylates and polychlorinated biphenyls (PCBs), several organochlorine pesticides and herbicides such as DDT, Atrazine, and Vinclozolin, and complex mixtures such as municipal wastewater effluents, agricultural runoff, and pulp and paper mill effluents (Hewitt and Servos 2001). Despite the wide ranging opinion on the impact of EDS on human beings and overall ecology, the adverse effects on aquatic species such as fish is well established. For instance, male fish living just downstream of municipal wastewater effluent discharge locations experience feminization through the development of egg proteins only found in females, reduced male hormone levels, and smaller gonad size (Desbrow et al. 1998).

EDS research in Canada, particularly studies on fish in the Great Lakes, has been essential in bringing this issue to the forefront. Among the major sites and sectors identified for potential endocrine disruption in the Canadian aquatic ecosystem were municipal effluents, intensive livestock production areas, and agricultural activities involving pesticides and herbicides (McMaster 2001). Surveys of municipal wastewater treatment facilities in several North American, South American, and European cities showed the presence of estrogens in final effluents (Baronti et al. 2000; Belfroid et al. 1999; Ternes et al. 1999). The high variation in the observed data suggests that particular treatment sequences and operational conditions within the plant significantly impact the extent of EDS release into the receiving water body. Very few studies have been conducted to correlate degree of complexity and type of specific practices within treatment facilities to biodegradation efficiency of EDSs (Planas et al. 2002; Ternes et al. 1999). The field data in European activated sludge treatment plants suggest that at common hydraulic retention times of 4-14 hours estrogens and alkylphenols cannot be completely eliminated (Johnson and Sumpter 2001).

Land application of animal manure and corresponding potential runoff to surface water bodies could have significant contributions to endocrine disruption. A study conducted to evaluate 17-b-estradiol runoff after poultry litter application to pasture revealed that this practice can substantially contribute to hormone runoff and that 17-b-estardiol persists in litter for at least 7 days under field conditions (Nichols et al. 1997). However, in laboratory microcosm studies conducted by Agriculture and Agri-Food Canada, estrogenic compounds as well as 4-nonylphenols were rapidly removed in agricultural soils under typical conditions (Colucci et al. 2001; Colucci and Topp 2001; Topp and Starratt 2000). Nevertheless, manure and sewage solids application to agricultural lands can act as a source for EDS if adequate pre-treatment is not provided or proper land application methods are not used.

It has been demonstrated that biodegradation kinetics of estrogenic substances such as 17-b-estardiol and enthynylestradiol are greatly increased when higher than naturally detected concentrations are available. Since estrogens bind readily to organic matter, their sorption is directly related to total organic carbon content present. MBRs could provide a suitable environment for EDS biodegradation due to high organic content in the mixed liquor and the retention of all particular and colloidal matter. In addition to accumulating the target compound behind the membrane, the MBR exposes it to high concentrations of biomass and allows for extensive bio-acclimation. The possibility of maintaining high solid retention times in MBRs leads to a diverse microbial culture which includes slow growing organisms capable of breaking down complex organic compounds (Cicek et al. 1999c). There is potential for intensifying the biological breakdown of estrogenic substances in membrane bioreactors. The same principles hold true for other EDS such as pesticides, herbicides, and toxic chemicals. For example, a selective extractive membrane bioreactor was utilized in a bench scale study on the treatment of wastewater containing 2,4-Dichlorophenoxyacetic acid (2,4-D), a chemical used as a herbicide or for preparation of other commercial herbicides. It proved highly effective and resulted in superior removal efficiencies compared to other biological treatment (Buenrostro-Zagal et al. 2000). In another study, an external membrane bioreactor was employed for high performance phenol degradation. Phenol degradation rates of up to 120 kg $m^{-3} d^{-1}$ were achieved with this system while allowing for improved control via independent adjustment of hydraulic and solid retention times. No toxic effects of high phenol concentration were observed (Leonard et al. 1998).

In a drinking water treatment application, a French company developed an industrial scale MBR system coupling biological denitrification and powdered activated carbon (PAC) adsorption of pesticides. Organic ultrafiltration membranes, consisting of double skin hollow fibers, were used and a plant of 400 m^3/d capacity was operated. PAC was continuously added to the reactor resulting in effluent concentrations of triazine compounds (atrazine, simazine, etc.) below detection limit and complete nitrate removal through denitrification (Manem 1996). In a separate study, immersed membrane filtration combined with PAC addition proved very effective in removing natural organic matter and synthetic organic chemicals from river water in Normandie, France (Lebeau et al. 1998). This system responded well to feed water quality variations and was determined to be suitable for upgrading existing clarifiers or sand filters.

These studies clearly outline the strong potential of the MBR technology in reducing ecological and health risks associated with endocrine disrupting substances including pesticides and herbicides. The utilization of MBRs in municipal wastewater treatment plants will ensure enhanced retention and biodegradation of natural and synthetic hormones. Industries involved in the production or processing of steroids, synthetic detergents, agricultural pharmaceuticals, herbicides, pesticides, and fungicides should consider membrane processes for wastewater treatment and water reuse. Hybrid processes that integrate membrane filtration and activated carbon adsorption present extremely effective alternatives for eliminating toxicity and carcinogenic potency in groundwater and drinking water sources.

Nitrate removal in drinking water

Denitrification and removal of natural organic matter are two main treatment requirements for drinking water. Nitrate is the most common groundwater contaminant in North America and world-wide (Kapoor and Viraraghavan 1997). Nitrate is a stable and highly soluble nitrogen species, easily transported and accumulated in groundwater systems. These properties, coupled with increased anthropogenic discharges of nitrogen containing compounds from point and non-point sources, have resulted in elevated nitrate concentrations in ground and surface waters. Non-point sources may have a larger impact on groundwater and are associated with agricultural and livestock practices and residential septic tank effluents (Bouchard et al. 1992; Kapoor and Viraraghavan 1997).

Nitrates can be removed either biologically or by physicochemical treatment techniques such as reverse osmosis, ion exchange, and electrodialysis. Natural organic matter can be treated biologically or through activated carbon adsorption. Biological removal of nitrates and organic matter is receiving more attention due to the complete conversion of nitrate into nitrogen gas and relative ease of operation (Falk 2002). Conventional physico-chemical treatment methods only concentrate nitrate into solutions which still require disposal. In typical biological dentitrification processes, however, post treatment processes such as sand filtration, activated carbon adsorption, and disinfection are required to remove biological entities and excess organic matter and color. The number of post-treatment processes can be significantly reduced by using a MBR for biological denitrification. All biological entities as well as some dissolved organic matter will be retained in the bioreactor while long denitrifying culture retention times and short hydraulic retention times can be maintained (Nuhoglu et al. 2002).

MBRs have been investigated on an experimental scale for heterotrophic denitrification of groundwater and drinking water using two significantly different configurations. One configuration employed the membrane as a cell recycle tool in an external MBR set-up (Barreiros et al. 1998; Delanghe et al. 1994), whereas the other configuration used the membrane as a semi-permeable ion exchange barrier for nitrate transfer (Fonseca et al. 2000; Mansell and Schroeder 1998; Velizarov et al. 2000). Up to 99% nitrate removal, despite unusually high nitrate loadings and low hydraulic retention times, were reported in these studies. Further investigation and optimization on larger scale systems are required to determine the economical feasibility of such processes.

CONCLUSIONS

The membrane bioreactor technology has great potential in wide ranging applications including municipal and industrial wastewater treatment, groundwater and drinking water abatement, solid waste digestion, and odor control. The technical feasibility of this process has been demonstrated through a number of pilot and bench scale research studies. Full scale systems are operational in various parts of the world and substantial growth in the number and size of installations is anticipated for the near future. The MBR process is already considered as a viable alternative for many waste treatment challenges and with water quality issues firmly placed into the forefront of public debate, ever tightening discharge standards and increasing water shortages will further accelerate the development of this technology.

Agricultural activities and related industries constitute a potential source of pollution to the environment. Waste from intensive livestock operations and wastewater generated by the food processing industry are two streams characterized by high organic and nutrient strength. Multiple treatment processes are normally required to ameliorate the waste to levels acceptable for on-site reuse or direct discharge to surface water. MBRs offer a proven alternative due to their ability to handle high organic loadings and wide fluctuations in flow and strength. Activated sludge scrubbing may also be able to be incorporated into these systems for odor control and air pollution management. High quality effluent produced by the MBR would provide pathogen and bacteria control and assist the facility in complying with strict environmental regulations. It would also allow extensive process optimization through internal water recycle and significantly reduce dependence to municipal waste treatment facilities or to the availability of crop land for waste application.

The presence of substances such as natural and synthetic hormones, industrial chemicals, pesticides, herbicides, and pharmaceuticals in ground and surface water bodies necessitates stricter control of point and non-point sources. Research studies indicate that certain configurations of MBRs would retain, concentrate, and consequently break down many of these compounds without requiring sophisticated tertiary treatment processes. The retention of all microbial entities and biological catalysts within the bioreactor allows for extensive biomass acclimation and enhanced reaction kinetics. Consequently, much improvement and attention toward membrane assisted hybrid processes for removing priority contaminants from effluents and drinking water sources is expected in the near future. As well, the positive barrier against biological entities provides a high quality product which is essential for potable water use. The possibility of combining the removal of organic matter, nutrients, toxic chemicals, and biological organisms in one treatment system is certain to fuel future research and development in this emerging field.

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