Paper No. 02-404

MEMBRANE BIOREACTORS IN THE TREATMENT OF WASTEWATER GENERATED FROM AGRICULTURAL INDUSTRIES AND ACTIVITIES

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Written for presentation at the
AIC 2002 Meeting
CSAE/SCGR Program
Saskatoon, Saskatchewan
July 14 - 17, 2002

Abstract

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. There have been numerous successful pilot-scale studies with some full-scale models in operation in France, the United States, and Japan. 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 can be treated with MBRs resulting in compact systems producing high quality reusable water. Also effective removal of nitrate, herbicides, pesticides, and endocrine disrupting compounds can be achieved by MBRs.

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ABSTRACT

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. There have been numerous successful pilot-scale studies with some full-scale models in operation in France, the United States, and Japan. 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 can be treated with MBRs resulting in compact systems producing high quality reusable water. Also effective removal of nitrate,

herbicides, pesticides, and endocrine disrupting compounds can be achieved by MBRs. **Keywords:** membrane filtration, wastewater, manure, food processing, endocrine disruptors, pesticides

INTRODUCTION

The demand for clean water is vast, whether be for human consumption, agricultural application, or industrial use. Recent problems in Walkerton, ON and North Battleford, SK as well as countless boiling water advisories issued across Canada 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 new 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. 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, municipal wastewater treatment for small communities, industrial wastewater treatment, and landfill leachate treatment (Manem and Sanderson 1996).

Several promising areas of application of MBRs remain unexplored and require detailed experimental evaluation. These 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. New configurations of bioreactors which would be multifunctional and be integrated into various treatment sequences need to be developed to expand the applicability and feasibility 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 industries and activities.

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 most popular. 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 (Metcalf&Eddy 1991). 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 standard, membrane systems regained interest.

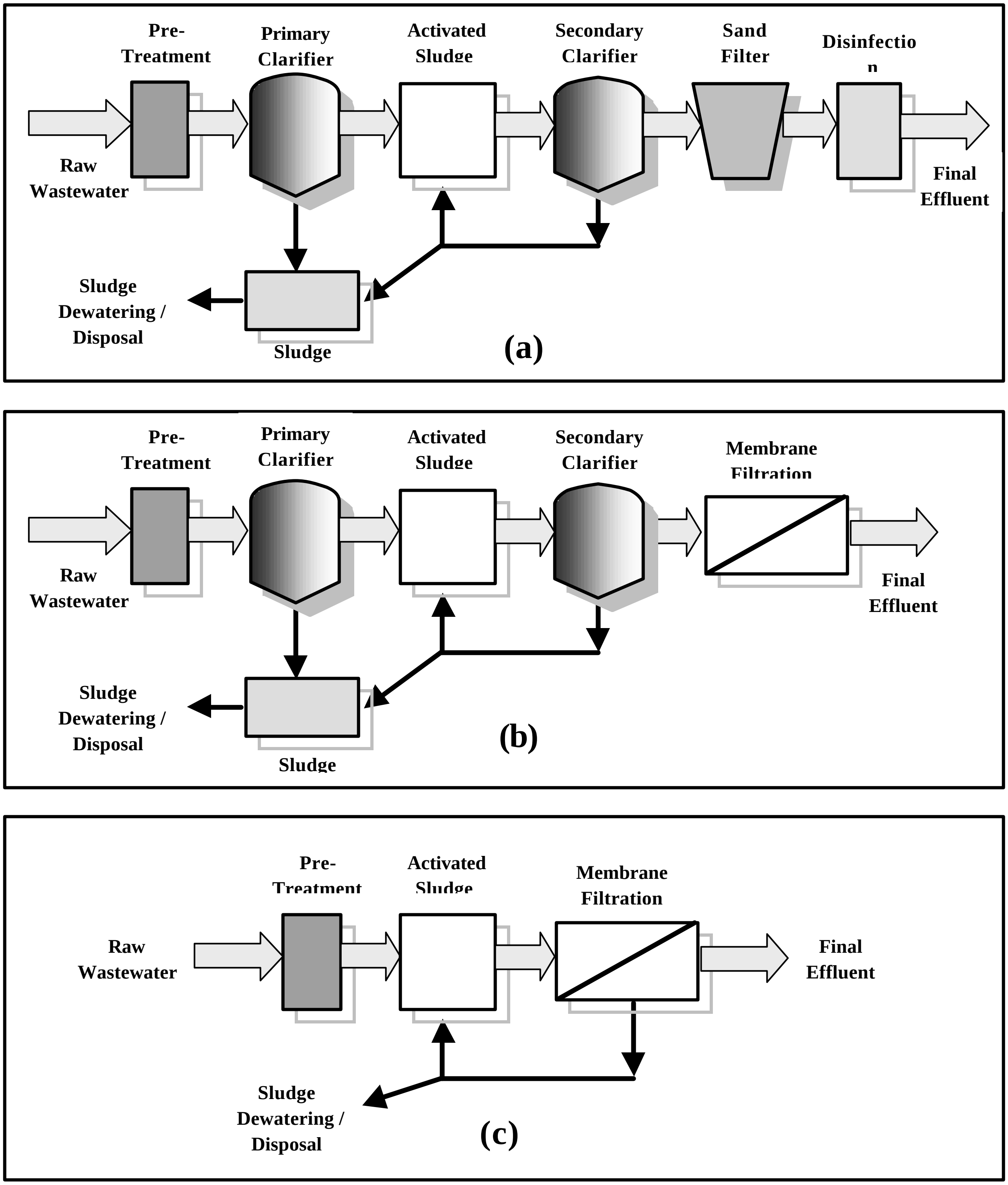

Figure1: Flowcharts for (a) conventional wastewater treatment, (b) conventional treatment including tertiary membrane filtration, and (c) membrane bioreactors

Membrane modules have evolved form 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 no suspended solids are lost in the clarification step, total separation and control of the solid retention time (SRT) and hydraulic retention time (HRT) is 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 sludge ages 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 and 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. 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 settlebility properties (Cicek et al. 1999c). Another limitation of the MBR, when operated at high SRTs, is the possible accumulation of non-filterable inorganic compounds in the bioreactor. This can reach concentration levels that can be harmful to the microbial population or membrane structure (Cicek et al. 1999a).

The MBR has emerged as an alternative treatment process, especially in cases where space and water resources are limited and high quality product water is required. Industrial wastewater, which is difficult to treat and requires long sludge ages, and wastewater operations where settling and clarification problems are regularly encountered are potential areas of application. With new developments in membrane design and the institution of more stringent discharge limits, MBRs have become feasible alternatives.

System Configurations and Membrane Selection

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, which is also commonly known as the integrated MBR, involves outer skin membranes that are internal to the bioreactor. The driving force across the membrane is achieved by pressurizing the bioreactor or creating negative pressure on the permeate side of the membrane (Buisson et al. 1998; Cote et al. 1997; Rosenberger et al. 2002). Figure 2 presents a simple schematic of the integrated (submerged) MBR.

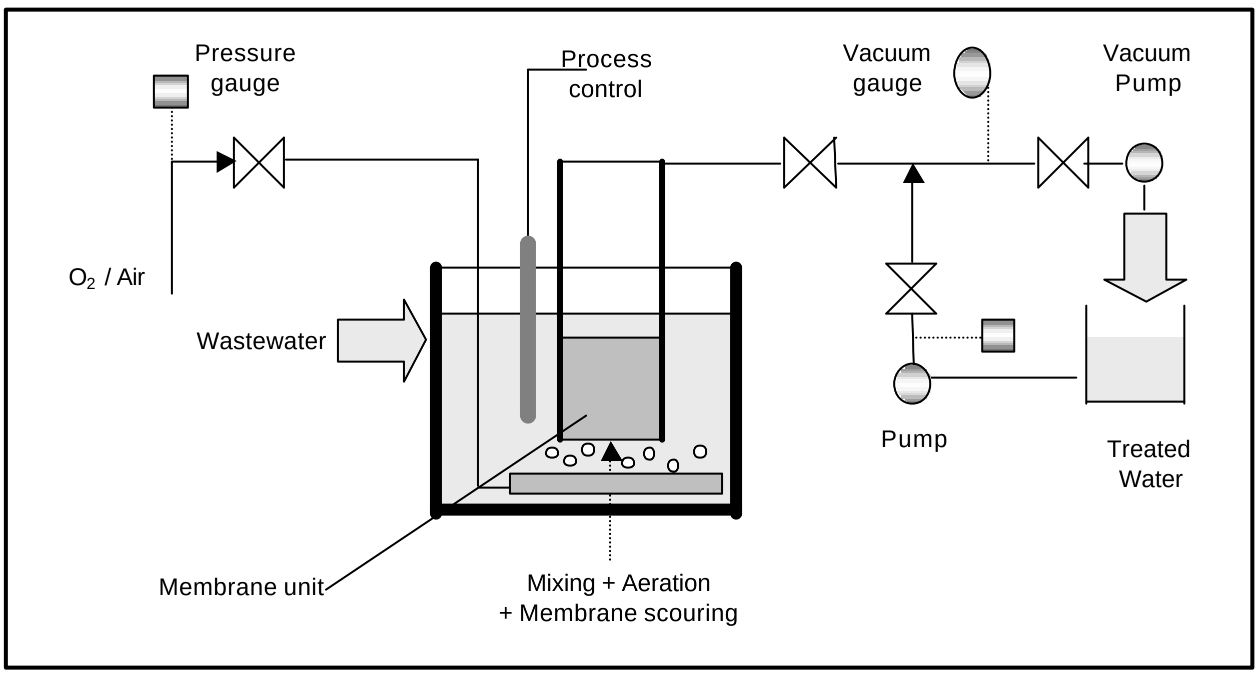

Figure 2: Schematic of Integrated (Submerged) MBR

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 air and liquid 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 to 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 Figure 3.

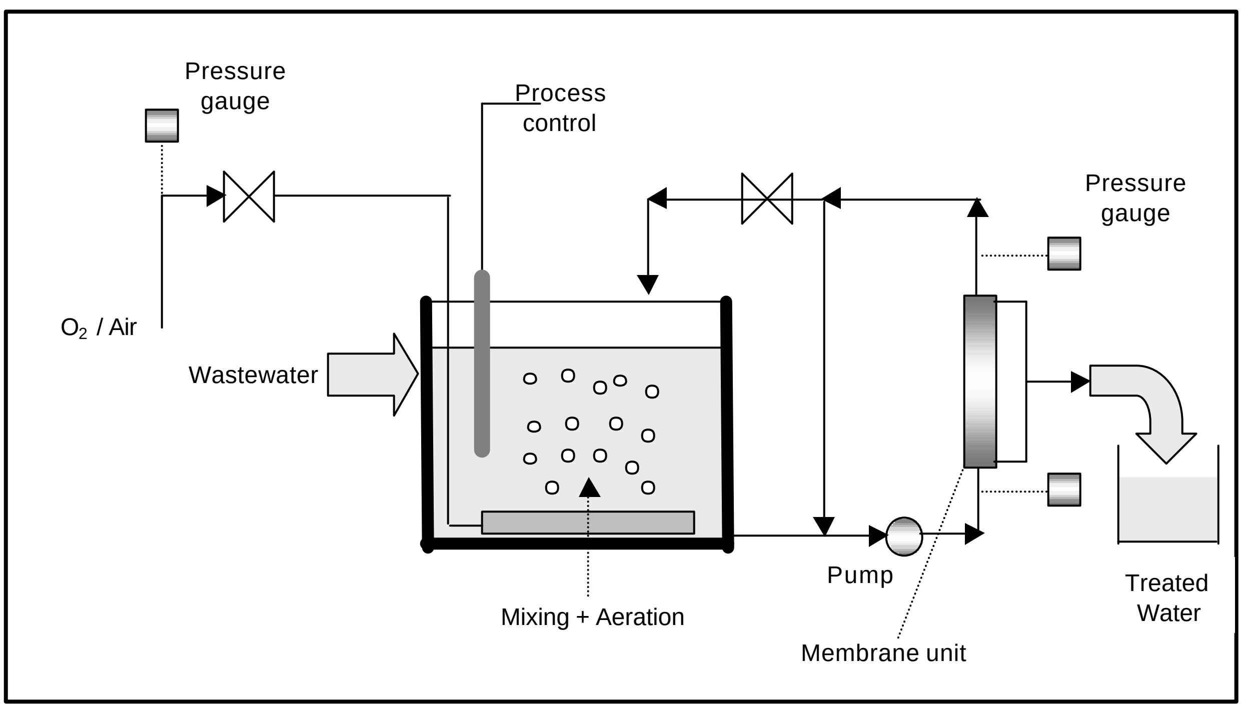

Figure 3: Schematic of Recirculated (External) MBR

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, polyolefin, etc), metallic, and inorganic (ceramic) micro-filtration and ultra-filtration membranes. The pore size of the membrane used ranged from 0.01 μm up to 0.4 μm (also reported in molecular weight cutoff as 20-2000 kilodalton). The fluxes obtained ranged from 0.05 to 10 m/d, 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 ^{o}C. The applied trans-membrane pressure ranges from 0.2 to 5.0 bar for inner skin membranes and from -0.1 to -0.8 bar for outer skin membranes (Manem and Sanderson 1996).

The membrane used in MBR systems must satisfy several criteria. It must be inert and non-biodegradable. It should be easy to clean and regenerate and should be resistant to cleaning agents, high temperatures, and pressures. Uniform pore distribution and high porosity are desired characteristics. The membrane should be neutral or negatively charged to prevent adsorption of microorganisms. Durability and easy replacement are also factors to be considered to reduce operational costs selection. The composition of the biological mixture to be filtered plays a crucial role in the selection of the membrane. For instance, the presence of strong inorganic crystals which can change the composition and structure of the membrane surface through abrasion should be avoided to prolong the life of composite ceramic membranes. In these applications either pretreatment of the influent wastewater or the utilization of polymeric membranes are recommended (Cicek et al. 1999a).

There are several operating parameters that influence the filtration capacity of the membrane in a MBR. Trans-membrane pressure (TMP), which is the average pressure gradient across the membrane, is linearly related to permeate flux until the filtration cake resistance is dominant. At this point, which is also referred to as the critical TMP, flux becomes independent of applied pressure (Cicek et al. 1998b). The cross flow velocity (CFV) is another parameter that is linearly related to permeate flux. Viscosity of the mixed liquor is also a very important factor in MBR performance. High viscosity affects the hydraulic regime, promotes head loss and increases operation costs. Since viscosity is a function of temperature, the filtration performance is strongly affected by variations in mixed liquor temperature. The physiological state of the biomass can significantly impact the filtration performance of the membrane. The community structure in the bioreactor influences the extent of flocculation, charge and structure of cells, and the concentration of exo-polymeric substances (EPS). It has been shown previously, that the extent of floc formation is directly related to the concentration of EPS, which influence the structure of the filter cake and the extent of fouling (Manem and Sanderson 1996). A strong correlation between soluble organic compounds, particularly soluble sugars and proteins, and permeate flux was established in a long term study conducted by the author (Cicek et al. 2002). Organic compounds smaller than 0.10 μm in size exhibited the strongest impact on filtration performance. Therefore, extensive membrane fouling and the need for frequent regeneration can be reduced if conditions favorable to enhanced biodegradation and less EPS formation are created. It quickly becomes apparent that the design of MBR systems involves the consideration of many factors. These factors can be biological, physical, or hydrodynamic in nature. Understanding the role of each of these parameters and their interactions is essential for effective design, optimization, and cost analysis of this technology.

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. Legislation in several parts of Japan, encouraging water reuse in large buildings, stimulated the development and application of alternative technologies. Thus, several types of MBR systems were implemented on a large-scale basis and were made available commercially (Kimura 1991).

The Japanese company MPC applied the Ultra Biological System (UBIS), originally developed by the French company Rhone Poulenc, to wastewater recycling in the Marunouchi Building in Tokyo. Plate and frame ultrafiltration membranes, connected to an aerobic bioreactor, were used to treat wastewater originating from kitchens and bathrooms. The treated water was then recycled and used for flushing of toilets. An effluent free of suspended solids and very low organic content (below 5 mg/L of BOD) was obtained consistently. To maintain the permeate flux at 100-120 $L/h.m^2$ a membrane regeneration frequency of 45 days was required. A total of 40 UBIS systems were installed, treating more than 5000 m^3/day of wastewater (Manem and Sanderson 1996).

Sanki Engineering in Japan developed a similar wastewater reclamation system (MSR), utilizing a combination of ultrafiltration and activated sludge processes. A large number of plants utilizing the MSR technology were successfully installed and maintained by Sanki Engineering (Yokomizo 1994).

Thetford Corporation in Ann Arbor, Michigan was the first company in the United States to develop a MBR system for the treatment and reuse of municipal wastewater. The process named Cycle-let Wastewater Recycling System, was composed of an anoxic and aerobic biological treatment system coupled to a tubular organic membrane (Irwin 1990). Activated carbon and ozone addition were performed to remove odor and prevent biological activity. This system was capable of reducing water use by 70-90 % and was applied in more than 30 locations in the United States. A similar system, using ceramic tubular membranes was developed by Lyonnaise des Eaux in France. A semi-industrial aerobic pilot-scale MBR was used to treat municipal wastewater at the Aubergenville Wastewater Treatment Plant, nearby Paris. Steady operation was achieved and complete nitrification, along with over 93 % of COD and suspended solids removal was accomplished (Fan et al. 1996).

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. These properties promoted the application of MBR processes which became highly feasible under such conditions. The MBR system replaced a rather complex set of treatment systems which incorporated denitrification, coagulation, filtration, and activated carbon treatment (Magara and Itoh 1991). In another study several full scale plants using the Activated Sludge and Membrane Complex System, which was a modification of the UBIS system and was composed of a multi-phase bioreactor for carbon and nitrogen removal and a filtration unit were implemented. Tertiary treatment involved a carbon absorption and dephosphatation step (Manem and Sanderson 1996) .

The application of the MBR technology in urban wastewater was limited to small treatment plants due to the high cost of the membrane units. Muller et al. (Muller et al. 1995) demonstrated that domestic wastewater from the city of Delft in the Netherlands could be successfully treated by an aerobic reactor coupled with a cross flow membrane. However, he concluded that the process was not economically feasible due to high pressure and aeration requirements. Pouet et al. (Pouet et al. 1994) showed that cross flow microfiltration can be an effective tertiary treatment method for urban wastewater depending on the choice of secondary upstream treatment. Further developments in membrane design and optimization, as well as the increasing number of companies entering the membrane market, should result in less expensive membrane units and stimulate the use of MBR systems in the treatment of urban wastewater.

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 sludge ages are required for effective solids destruction. It has been proven that the addition of a microfiltration unit will enhance the performance of the digester by decoupling the HRT and the SRT and, thereby, allowing higher volumetric throughput. An economic evaluation of such a MBR process was performed at a wastewater treatment plant in Durban, South Africa. It was shown that the MBR system could reduce both the capital and operational cost of a conventional anaerobic digester (Pillay et al. 1994).

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. The first anaerobic MBR system was developed by Dorr-Oliver and was known as the Membrane Anaerobic Reactor System

(MARS) (Sutton et al. 1983). In Japan, a commercial scale anaerobic fixed-growth reactor in combination with ultrafiltration membranes was used for the treatment of wool-scouring effluents. A 70 m^3/d capacity commercial plant with a reactor volume of 500 m^3 and an effective membrane area of 80 m^3 was built and was successfully operated for several years (Hogetsu et al. 1992).

In Japan=s Aqua Renaissance ›90 project, a wide variety of different configurations of anaerobic MBRs were used for the treatment of industrial wastewater and sewage. The objective of this project was to develop low cost, space saving treatment processes to produce reusable water. Wastewater containing fat, wheat starch, and pulp and paper wastes were successfully reclaimed by various pilot plant MBR systems (Kimura 1991; Minami 1994). Generally, COD removal rates of over 90 % were obtained while high SRTs and biomass concentrations were maintained in the bioreactor.

The use of aerobic membrane bioreactors in the treatment of industrial wastewater is fairly recent compared to anaerobic processes. Degremont developed an aerobic bioreactor coupled with ceramic ultrafiltration membranes. This system was applied at the Lancome plant in the north of France for the treatment of cosmetic processing effluents. The high quality of treated water obtained from this process enabled direct reuse at the same facility (Manem and Sanderson 1996). At the University of Stuttgart in Germany, a pressurized aerobic bioreactor in combination with organic membranes was developed and optimized (Krauth and Staab 1993). In this application, oxygen transfer was optimized and high solid retention times were maintained for low sludge production.

A full scale aerobic MBR system was operated at the General Motors manufacturing facility in Mansfield, Ohio, for the treatment of wastewater containing synthetic metalworking fluids and high amounts of oil and grease. An average of 116 m^3/d of wastewater (all of the plants wastewater) with an organic loading rate of 6.3 kgCOD/m^3/d was processed. An average of 94 % of COD removal and considerable reductions in oil and grease were achieved (Knoblock et al. 1994). In another study involving oily wastewater for a metal transformation mill, a membrane bioreactor further reduced biological toxicity of the effluent by 10 fold and reduced overall quantity of hazardous waste by 3 fold (Zaloum et al. 1994). Elsewhere, synthetic wastewater containing fuel or lubricating oils and surfactants was biodegraded with high efficiency using a bioreactor coupled to ultra-filtration membranes. Up to 99.99 % removal rates at a hydraulic retention time of 13.3 hours was achieved (Scholzy and Fuchs 2000).

Dufresne compared the performance of an aerobic MBR with a conventional activated sludge system for the treatment of a chemico-thermomechanical pulping effluent. He concluded that the MBR was superior to the conventional system in COD, suspended solids, and toxicity removal (Dufresne et al. 1998). In another study involving the treatment of mechanical newsprint mill wastewater a MBR exhibited higher removal rates than an ultrafiltration system alone (Ragona and Hall 1998). MBRs also proved effective in removing organic compounds and odourous contaminants such as hydrogen sulfide and methyl mercaptane from kraft pulp mill evaporate condensate. This would enable the reuse of this condensate in several processes within the plant in place of fresh water (Berube and Hall 2001).

Another application of MBR systems in industry is in the area of landfill leachate treatment. 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. For instance, the plant operated by Dectra in France treats 50 m^3/d of landfill leachate with a combination of MBR and RO processes (Manem and Sanderson 1996).

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 recent government studies in Ontario and Quebec concluded that the industry was not environmentally sustainable at the current rate of expansion. The growing concern is the environmental impact of waste generated in these facilities in the form of manure, wastewater, unpleasant odors, ammonia, and methane. Current waste management systems 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. The public is becoming increasingly concerned with the livestock industries impact on surface and groundwater sources and air quality which will ultimately increase pressure on stricter government regulations. Therefore, there is great interest in developing alternative waste treatment systems to either reduce the extent of pollution or completely change current practices.

Most recently, intensive livestock operations have combined solid and liquid waste in a manure slurry form and have extensive ventilation systems to discharge odors. 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 energy friendly. A submerged aerobic membrane bioreactor could 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 could be utilized. Nitrogen is usually the key nutrient in livestock waste management and a treatment process incorporating nitrification and denitrification is essential. Either intermittent aeration or an anoxic department within the bioreactor can be employed for improved total nitrogen removal (Cheng and Liu 2001). Metal salts can also be added to reduce phosphorus content in the final effluent. Stability, biological diversity, capacity for treating high organic and nutrient loadings make the MBR technology a perfect fit for this purpose. MBRs are capable of producing effluent free of suspended solids, bacteria, and pathogens, allowing direct re-use of the product water in the livestock facility as wash-water. The reduced amount of sludge wasted from the MBR due to high solid retention times can then be recycled to the anaerobic digester or lagoon.

Aerobic activated sludge reactors a have been used on a limited scale as bio-scrubbers for the treatment of odorous air (Bowker 2000). Despite numerous positive reports form full-scale applications in North America, little data is 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. 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, the mere pressurization and introduction of this waste stream into an aerobic submerged MBR 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 eliminate the dependency of livestock producers on crop land, remove unpleasant odours from intensive livestock operations, reuse water on-site and thereby substantially reduce water use, and reduce environmental risks associated to manure application.

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. 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 will 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. A full scale membrane assisted anaerobic plant was developed and used for wheat-starch processing effluents in Ashford, England (Butcher 1989). At a cheese plant, a pilot-scale suspended-growth anaerobic reactor coupled with ultrafiltration membranes was successfully employed for the treatment of wastewater containing whey (Sutton et al. 1983). In another application, tubular ultrafiltration membranes were coupled with an anaerobic digester to treat high strength effluents from an egg processing plant. This system was called the Anaerobic Digestion-Ultrafiltration (ADUF) process and was developed in South Africa. It was demonstrated to be effective in producing colloid free effluent at a mean COD removal efficiency of 97 % for maize-processing wastewater (Ross et al. 1992). The same process was also employed in the treatment of a brewery effluent (Strohwald and Ross 1992).

In Japan, researchers investigated the treatment of liquor production wastewater using a pilot-scale anaerobic MBR system for 190 days. 98 % COD removal was obtained at a COD loading rate of 7 $kg/m^3.d$. Low biomass production rates and high methane generation were observed (Nagano et al. 1992). In another study, a laboratory scale experiment on the performance of an activated sludge system coupled to a rotary disk ultra-filtration membrane in the treatment of high strength fermentation wastewater was investigated. The wastewater contained a TOC of 10,000 mg/L and ammonia of 1,400 mg/L and removals of over 94% and 96% respectively were observed. Also, intermittent aeration was implemented to further increase total nitrogen removal by denitrification (Lu et al. 2000).

In the case of a food ingredients manufacturing company, the existing conventional activated sludge treatment system was not capable of handling large variations in wastewater COD (1200-12000 mg/L) and total nitrogen (300-800 mg/L). The continually changing biomass settling behavior led to high maintenance and operation cost and a submerged MBR was evaluated as a replacement. The pilot system 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 (Cantor et al. 1999).

Most studies were conducted in Japan, South Africa, and France, where water shortages exist and space is limited. The vast majority of the studies concluded that the MBR was promising yet too costly and impractical for large flows. All of these pilot and bench scale systems investigated external membrane units which were characterized by high energy consumption and expensive filtration modules. The emergence of submerged MBRs that utilize fairly economical polymer-based membranes and require much less energy has revolutionized municipal wastewater treatment and has tremendous potential in larger scale, high volume throughput facilities across the globe. Very few studies however have been conducted on the applicability and efficiency of submerged MBRs for food processing effluents. 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 and energy 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 without doubt justify consideration of the process in food processing facilities.

Endocrine Disrupting Substances, Pesticides, and Herbicides

The most recent study by 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 Environment Protection Act in 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 run-off to surface water bodies can have significant contributions to endocrine disruption. A study conducted to evaluate 17-b-estradiol run-off after poultry litter application to pasture revealed that this practice can substantially contribute to hormone run-off and that can 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.

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 tremendous 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 for commercial herbicide preparation. 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} day^{-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 and Sanderson 1996). In a separate study, immersed membrane filtration combined with PAC addition proved very effective in removing natural organic matter and synthetic organic chemicals form 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 to 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. In intensely farmed areas of rural Canada the groundwater nitrates levels are increasing. In many EU countries nitrate concentrations exceed all guidelines and nitrogen exclusion zones are introduced.

Nitrates are 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. 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 and economical 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 major 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 can also be incorporated into these systems for odor control and air pollution management. High quality effluent produced by the MBR would guarantee 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 fool proof technology that assures 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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