Application of Membrane Bioreactor Technology to Wastewater Treatment and Reuse

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Abstract

During the next twenty years the availability of fresh clean water will become severely limited in many areas of the world. Water scarcity and water quality are problems facing both developed and undeveloped countries. Salinity intrusion into ground water supplies, nutrient eutrophication, endocrine disruptors and heavy metals are just a few sources of contamination that may be encountered in water supplies. One possible solution to these problems is the application of membrane bioreactors (MBR) for wastewater treatment and reuse. Membrane bioreactors provide the benefits of biological treatment with a physical barrier separation. Compared to conventional treatment processes, membranes are able to provide better quality effluent with a smaller, simplified treatment process.

Membrane treatment is an advanced process that has become increasing popular over the past ten years. Membrane processes have been understood but unutilized since the 1960’s due to high capital costs (Fane, 1996). Recent developments in membrane manufacturing allow the production of better quality membranes at a reduced price. Combined with increasing conventional water treatment costs, membrane treatment is now considered economically viable for municipal and industrial treatment.

Keywords

Membrane bioreactor, membrane, microfiltration, water reuse, water recycling

Introduction

In the near future the availability of fresh clean water will become increasingly limited in many areas of the world, at the same time an increasing quantity and quality of water will be required to maintain and support the growing population. Many under developed areas of the world already face a shortage of clean drinking water and irrigation water for food production, while in industrialized nations, such as the U.S., the quality of available water for public and industrial use will be a larger issue.

Portions of Africa, Asia, India, China, Australia, Europe, Mexico, the Middle East, and southwest United States are identified as having a water scarcity, (Figure 1) defined as a supply less than 200 m^3/person/year (Howell, 2004). Areas with adequate supplies may face issues with quality. Salinity intrusion into ground water supplies, nutrient eutrophication, endocrine disruptors, and heavy metals are just a few sources of contamination that may be encountered in water supplies. One possible solution to these problems is the application of membrane bioreactors (MBR) for wastewater treatment and reuse.

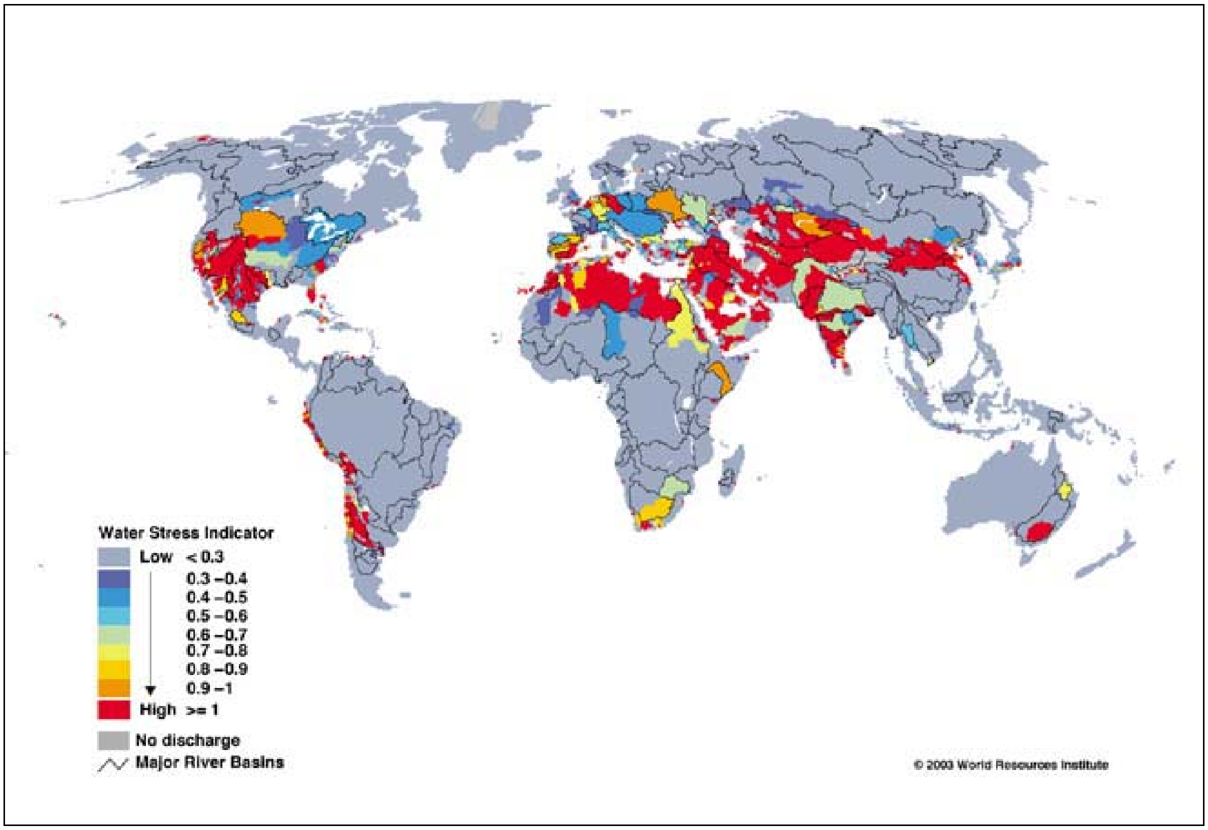

Figure 1: Areas Stressed due to Water Demand (World Resources Institute, 2003)

The recycling or reuse of wastewater is one way of supplementing available water supplies. The recent developments in membrane technology have made the recycling of wastewater a realistic possibility. Effluent from membrane treatment is able to meet or exceed current drinking water regulations. Despite the high quality, the reuse of water faces several hurdles. The perception of recycled water by the public is less than favorable. In the U.S. the public is generally accepting of the reuse of water for irrigation, but strong opposition of its use for drinking water has been encountered. In areas with greater water scarcity, such as Singapore, the acceptance of recycled water is much greater (Howell, 2004). The additional treatment required for reuse comes at an increased cost, which may not be justified in areas with sufficient water supplies. Although once considered uneconomical, membrane technology costs have decreased by 80% over the past 15 years, making the use of membranes and MBR a viable option for the first time (Layson, 2004).

Membrane bioreactors are able to provide the benefits of biological treatment with a physical barrier separation. Compared to conventional treatment processes, membranes are able to provide better quality effluent with a smaller, automated treatment process.

Membrane Characteristics

Membrane treatment is an advanced treatment process that has become increasing popular over the past ten years. Membrane processes have been understood but underutilized since the 1960's due to high capital costs (Fane, 1996). Recent developments in membrane manufacturing have enabled the production of better quality membranes at a reduced price. Compared with increasing conventional water treatment costs, membrane treatment is now considered economically feasible.

Filtration Processes

There are six commercially used membrane separation processes; Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), Reverse Osmosis (RO), Dialysis, and Electrodialysis (ED). Membrane processes can be classified based on membrane separation size and mechanism, membrane material and configuration, or separation driving forces used. Membrane processes utilize set terminology to discuss membrane performance. The rate of fluid transfer across the membrane is referred to as the flux, and has units of kg/m^2h.The pressure experienced across the membrane is referred to as the trans-membrane pressure (TMP). The fluid that passes through the membrane is the permeate, while the flow retained by the membrane is the retentate (Tchobanoglous, et al., 2003).

Separations based on membrane pore size include MF (0.1- 0.2 µm),UF (0.002 – 0.1 µm), and NF (0.0001 – 0.001 µm). The ranges are not strictly defined and some overlap exists. These three types of filtration rely on a sieving action to remove particulate matter. In comparison RO membranes have a pore size of 0.0001 – 0.001 µm, but rely on the rejection of small particles by an adsorbed water layer rather than physical straining (Tchobanoglous, et al., 2003). All four varieties of membranes rely on hydrostatic pressure differences to drive the separation process. Microfiltration or Ultrafiltration is the most commonly used membrane size in wastewater and MBR treatment. Microfiltration is able to remove protozoa, bacteria and turbidity, while UF has the added benefit of virus removal (Howell, 2004).

Membrane Materials

Membranes are made from either organic polymers or ceramic materials. Polymers offer the advantage of low cost production but may contain natural variations in pore size, and are prone to fouling and degradation. Ceramic membranes offer excellent quality and durability but are economically unfeasible for large scale operations, although they may be well suited for industrial applications (Scott and Smith, 1996). All of the commercial MBR manufacturers use polymeric MF membranes. Table 1 lists the most common types of polymer materials used to construct membranes. Polymeric membranes are manufactured in several forms, the most common types for MBR are hollow fiber and plate and frame. Hollow fiber membranes are extruded into long fibers and joined into bundles, called modules. The modules are submerged in the wastewater and permeate is drawn into the center of the fiber by an applied vacuum. Plate and frame modules are made from large membrane sheets loaded into cassettes. Permeate is drawn through the membrane due to an applied pressure differential. Thin layer polymeric membranes may be laminated to a thicker porous surface to provide additional strength and support (Fane, 1996).

Table 1: Polymer Membrane Materials and Characteristics (Layson, 2004)

Material	Abbr.	Advantages	Disadvantages
Polypropylene	PP	Low cost High pH range tolerance	No chlorine tolerance Expensive cleaning chemicals required
Polyvinylidene fluoride	PVDF	High chlorine tolerance Simple cleaning chemicals	Cannot sustain pH > 10
Polyether Sulphone & Polysulphone	PES/PS	Chlorine tolerance Reasonable cost	Brittle material requires support or flow inside to outside
Polyacrylonitrile	PAN	Low cost, typically used for UF membranes	Less chemically resistant than PVdF.
Cellulose Acetate	CA	Low cost	Narrow pH range Biologically active

Membrane Configuration

Flow within a membrane system can be either cross-flow or dead-end. In cross-flow the flow of wastewater is parallel to the membrane surface and helps to reduce fouling from particulate matter. Water not withdrawn as permeate is recycled and mixed with the feed stream. In dead-end flow the water is fed perpendicular to the membrane. All of the water applied to the membrane must pass through the membrane, or be rejected as waste. MBR systems use cross-flow due to the high particulate level of the waste and reduced fouling potential (Alexander et al., 2003).

Membrane systems can be designed with either individual pressurized or submerged modules. Submerged systems are becoming the industry norm due to the associated advantages. Submerged systems have reduced capital cost since the need for module housing and pressure manifold is eliminated. The space requirement for a submerged system is half that for a pressurized system, allowing high rate systems in small spaces. Submerged systems are limited to a maximum TMP of 80 kPa, since the high pressure side is open to atmosphere. Pressure systems are able to operate with a TMP up to 150 kPa, but this additional range rarely justifies the additional capital expense (Layson, 2004). Most MBR systems are operated as submerged systems, with outside to inside flow hollow fibers and air/water backwashes. Due to the high solids loading MBR membranes are designed with a lower packing density, pore size and flux rate than water treatment membranes (Alexander et al., 2003).

Membrane Integrity

Monitoring membrane integrity is necessary for all processes. Membrane breakage or degradation can lead to the loss of physical separation and possible contamination of the effluent. Membrane integrity can be monitored by particle counters or pressure decay testing (PDT). PDT is the preferred method due to its reliability and increased accuracy. In PDT the membrane module is pressurized to a high pressure and monitored for leaks, the PDT is sensitive enough to detect the breakage of a single fiber (Layson, 2003).

Membrane Fouling

Membrane fouling is the largest concern in the design of membrane and MBR systems. Membrane fouling can be due to particulate build-up, chemical contamination or precipitation. Particulate fouling occurs as matter in the wastewater collects on the surface of the membrane. As the layer builds up the membrane pores can be blocked reducing the flux through the membrane and increasing the TMP. Particulate matter can foul membranes by either plugging or narrowing the pores or through the formation of a cake layer on the surface. Membrane fouling can be controlled through the use of periodic maintenance back-flushing and chemical cleans in place (CIP). Back-flushing is completed by reversing the flow of air or water through the membrane to unclog the pores. If the membrane is heavily fouled a chemical clean may be necessary. Sodium hydroxide and surfactant solution is the most common chemical used for cleaning, but other chemicals such as citric acid, chlorine, hydrogen peroxide, or aluminum bifluoride may be used depending on manufacturer’s guidelines. Long term fouling due to the precipitation of manganese of silica has been observed in some instances, but can generally be reversed with cleaning (Layson, 2003).

In membrane bioreactors several additional steps are taken to reduce fouling due to the high suspended solids in the retentate. Coarse bubble aeration is introduced at the bottom of hollow fiber membranes and travels vertically along their length. This has a two-fold purpose of aerating the wastewater and vibrating the membrane fibers to remove particulate matter, increasing the time between cleanings. The membranes are operated near critical flux to minimize fouling and in a periodic fashion, with a back-flush every 5 to 15 minutes (Howell, 2004).

Membrane Bioreactor

Water reuse with membrane started with the microfiltration of clarified secondary effluent. This process produced high quality recycled water, but acted as a tertiary treatment step. The development of MBR technology eliminated the need for large clarification basins. In an MBR system a membrane train replaces a traditional settling basin in a conventional system. Figure 2 illustrates the difference between conventional and membrane treatment options for water recycling. The main advantage of using membranes is the complete physical retention of suspended solids from the permeate. In a conventional activated sludge treatment system the quality of the effluent is dependant on the settling characteristics of the biomass. This requires the development of well settling bacteria, which can be difficult to maintain and may not be the ideal bacteria for treating the waste water. The MBR system prevents the loss of biomass, eliminating the need for a settling biomass, allowing a waste specific biomass to develop (Scott and Smith, 1996).

Conventional systems are limited to solids concentrations of 5 g/L or less due to hindrances encountered during solids settling. MBR systems are able to handle solids concentrations between 5 and 25 g/L, allowing much longer solids retention times within a reduced foot print (Xing et al., 2000). In addition, the MBR system allows the complete separation of hydraulic and solids retention times, enabling greater process control and adjustment.

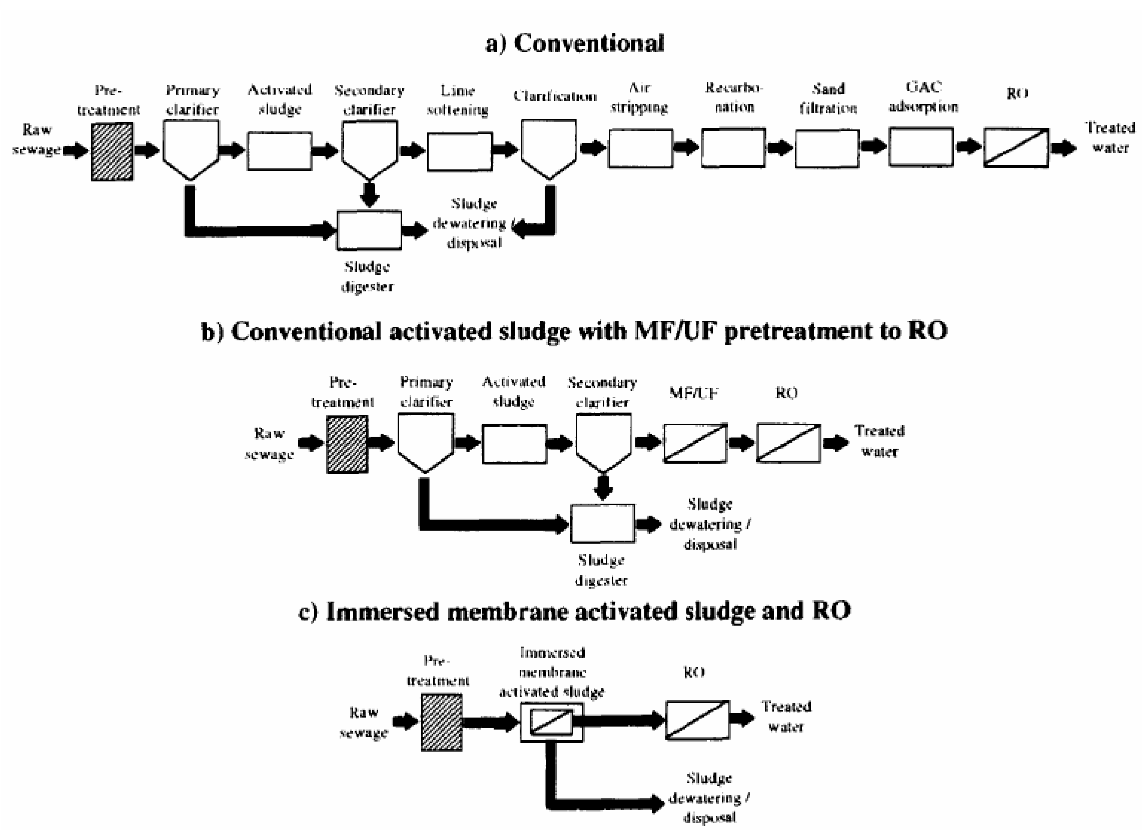

Figure 2: Comparison of Conventional and Membrane Treatment Trains (Cote, et al., 1997)

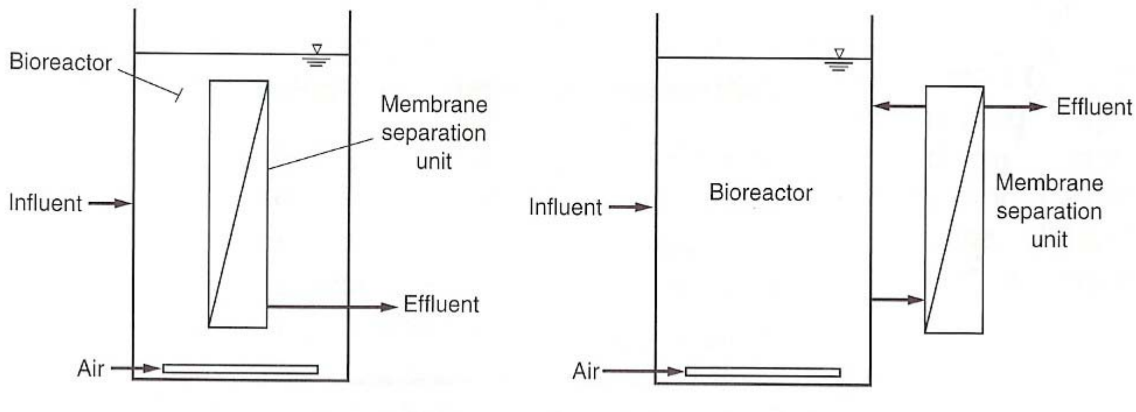

Figure 3: Basic MBR Designs (Tchobanoglous, et al., 2003)

There are two main designs for MBR plants as shown in Figure 3. The membranes can be submerged directly in the bioreactor, or submerged in multiple side tanks with a constant recirculation of wastewater. The advantage of the first set-up is a smaller foot print and capital cost. The second design is used most because it allows the shutdown of part of the system for membrane or tank maintenance without stopping treatment completely, and flow from multiple aeration basins can be directed to a single membrane basin. The design and selection of an MBR process is dependant on a number of design considerations and is based on the individual project.

Pretreatment

Feed water to the system undergoes pretreatment which generally involves primary clarification or screening with 0.5 – 3 mm screens to remove large particles and debris. The level of screening and waste water constituents may affect the process chosen. Fibrous materials such as hair and textiles may be able to pass through standard screens, while grease or oils may plug fine screens. The addition of a coagulant may be needed to condition the filter cake and improve flux (Layson, 2003).

Flux Rate

The ideal flux rate of an MBR system is dependant on the wastewater characteristics. Pilot testing is essential for determining design flux rates, due to the wide variation in fouling rates experienced between sites. The choice of an appropriate flux rate can have a dramatic impact on membrane life and cleaning frequency. Standard flux rates between 50 and 200 L/m^2h have been reported (Xing et al., 2001). The MBR system should be designed to handle peak flows of the system to prevent flooding of the system. Alternatively an equalization basin may be needed if the membrane flux rate is inadequate.

Substrate and Solids Removal

One of the main advantages of MBR systems is 100% removal of suspended solids from the effluent. MBR systems are also well suited for treating high strength wastewater with COD and BOD loads up to 13,000 mg/L and 6,500 mg/L, respectively (Scott and Smith, 1996). COD removals ranging from 89 to 97% have been reported (Pankhania et al., 1999; Scott and Smith, 1996; Rosenburger et al., 2002; Xing et al., 2000; Xing et al., 2001). Further investigation revealed that the majority of COD removal occurred in the bioreactor with the membrane separation contributing 8 to 12% of the total removal (Xing et al., 2000; Xing et al.,2001).

Table 2: Typical MBR Effluent Quality (Tchobanoglous, et al., 2003)

Parameter	Units	Typical Concentrations
Effluent BOD	mg/L	<5
Effluent COD	mg/L	<30
Effluent NH3	mg/L	<1
Effluent Total N	mg/L	<10
Effluent Turbidity	NTU	<1
Effluent P*	mg/L	<0.5

* with chemical P removal

Nutrient Removal

MBR systems operate aerobically due to the air bubbles used to clean the membrane fibers, and rely on heterotrophic bacteria for BOD and COD reduction. The aeration rate of an MBR system is controlled by the air flow needed to clean the membranes. Due to the high aeration rate in the membrane tanks the dissolved oxygen concentration of the return flow can reach 6 mg/L (Crawford and Lewis, 2005). Ammonia present in the feed water is converted to nitrate in the aerobic tank. Ammonia-nitrogen removals ranging from 96 to 98% have been reported (Xing et al., 2000; Xing et al., 2001; Scott and Smith, 1996) Typical MBR effluent quality is shown in Table 2.

The high dissolved oxygen concentration can be detrimental to denitrification which requires anoxic conditions to proceed. Denitrification can be achieved by creating anoxic zones within the bioreactor basin, but care must be taken to prevent the introduction of air within the recycle streams. Biological phosphorous is difficult but possible in an MBR system, the recycle streams must be carefully designed so that nitrate and oxygen does not contaminate the anaerobic zone (Crawford and Lewis, 2005). A general process diagram for biological phosphorous removal is shown in Figure 4. Phosphorous removal is more commonly completed chemically by iron co-precipitation adsorption through the addition of ferric chloride coagulant.

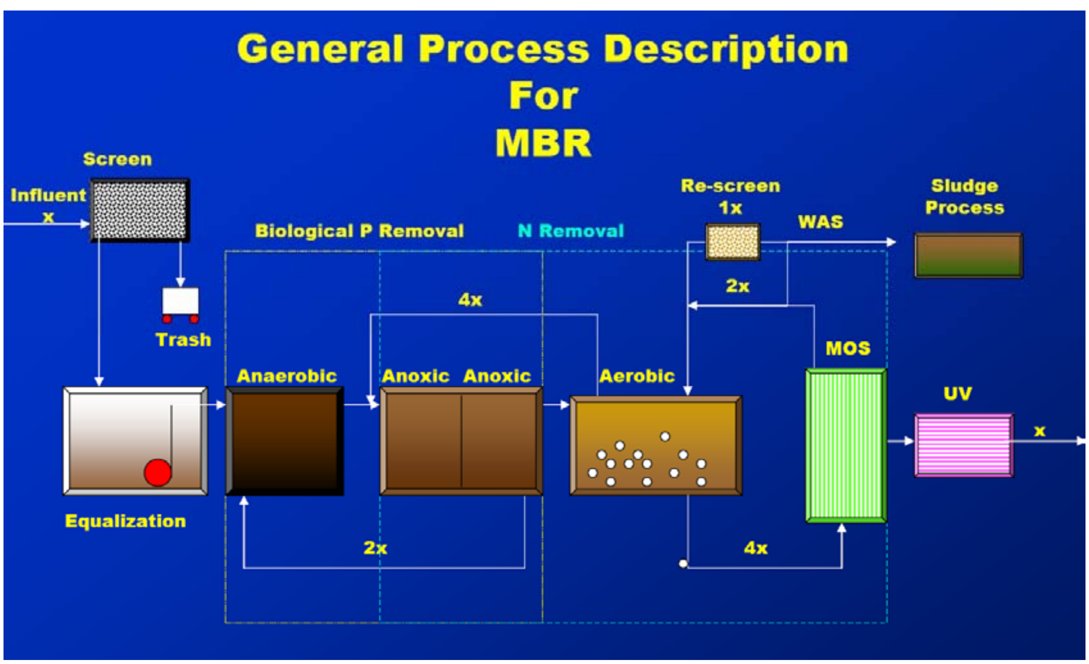

Figure 4: MBR Biological Phosphorous Removal Design (www.usfilter.com)

Solids Management

MBR systems are designed with SRTs ranging from 5 to 30 days. Due to the long sludge ages and the low F/M ratio, biomass production is approximately half that of a conventional system. Over time the biomass concentration within the tank will reach steady state without sludge wasting. Because of the accumulation of grit and inorganic solids in the tanks periodic wasting of solids is required. This wastage will be significantly less than a conventional system due to the increased biodegradation. Rosenburger et al., (2002) found that settled sludge in the bottom of the aeration tanks contained 60% inorganic particulate. MBR systems are also prone to foam formation on the tops of the bioreactors and provisions must be made for removal.

MBR Applications

MBR treatment is applicable to many sectors, including municipal, industrial, and water reclamation. The use of an MBR process for water reclamation can reduce the demand for potable quality water on local supplies, and reduce pollution from waste discharges into local water bodies.

Municipal Treatment

The filtration of municipal activated sludge is an ideal application for MBR treatment, Research completed by Rosenberger et al., (2002) found that an MBR system could be used to treat municipal waste water. A Zenon pilot MBR was operated for 535 days to study the treatment characteristics of the system. The pilot unit was equipped with three compartments for aeration, filtration, and denitrification, as shown in Figure 5. Hollow fiber Zeeweed membranes with a 0.2 µm pore size were used, with a 35 second back-flush every ten minutes. A maximum TMP of 0.5 bar was allowed. The raw wastewater had a mean concentration of 786 mg/L COD, 49 mg/L NH_4-N, 12 mg/L PO_4-P, and MLVSS of 32%. The HRT varied from 10.4 to 15.6 hours, with a corresponding volumetric loading rate of 1.1 to 1.7 kg COD/m^3d. The MBR system was found to achieve 100% suspended solids removal, 95% COD reduction, 100% nitrification, and 82% denitrification. These results correlate with pilot studies completed by Cote et al., (1997) in Indio, California and Maisons-Laffitte, France. In addition 6 log removal of total coliforms and 4 log removal of bacteriophages were found.

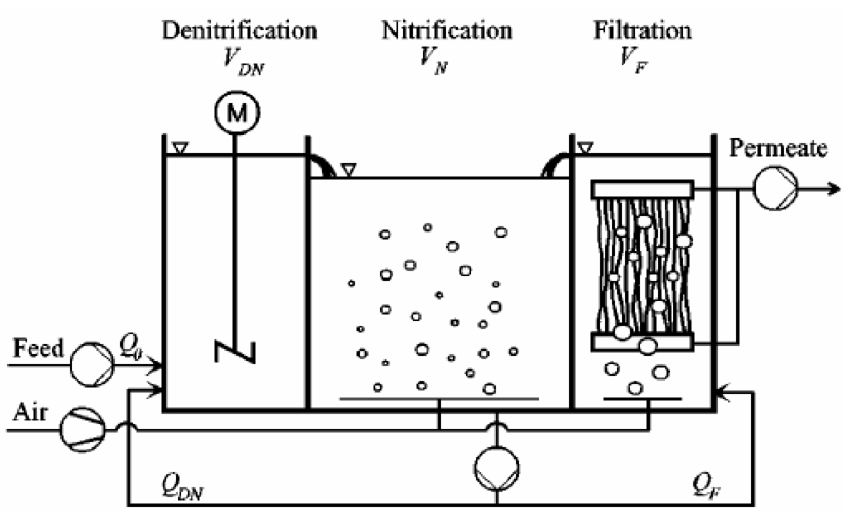

Figure 5: Pilot Municipal Treatment MBR Process Schematic (Rosenberger et al, 2002)

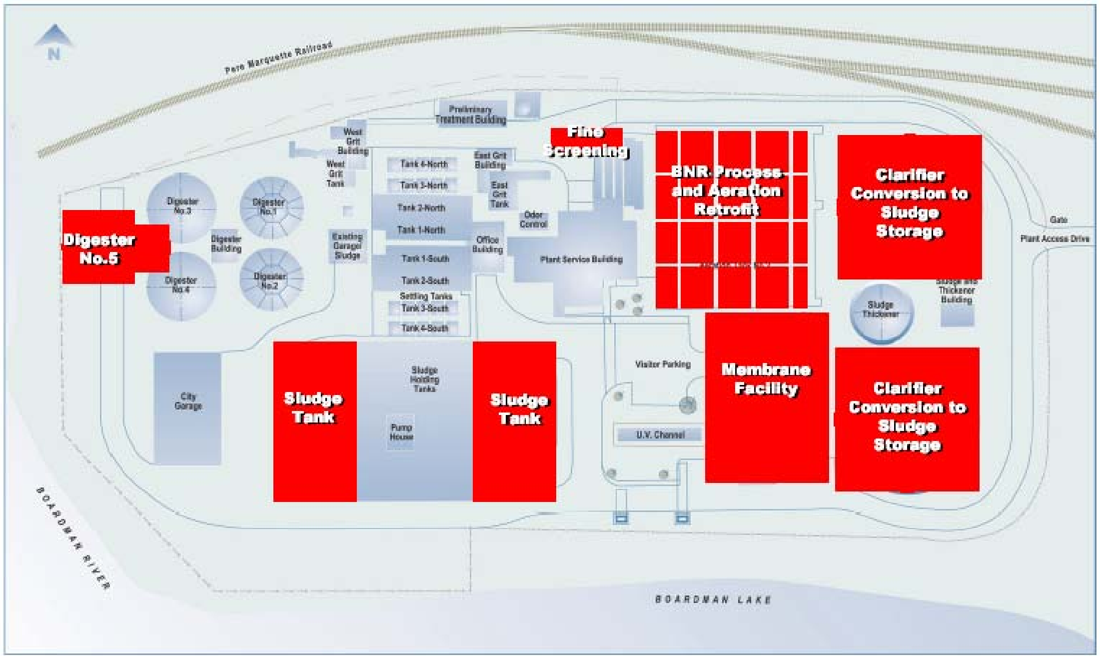

Figure 6: Traverse City MBR Design Layout (Crawford and Lewis, 2005)

The largest operating municipal treatment MBR system in North America is located in Traverse City, Michigan and capable of treating 8.5 MGD. Expansion of the conventional wastewater treatment plant began in 2002. The site was severely limited in the amount of space for expansion. Given the community desire for high quality effluent, MBR was the ideal choice. The use of MBR technology allowed a 40% increase in capacity within the same footprint (Figure 6). The biological nutrient removal process used was a modified University of Cape Town flow configuration. The process was designed with three recirculation zones due to the high DO concentration in the membrane tank (Figure 7). The MBR unit began operation in summer 2004 and is able to achieve effluent phosphorous concentration of 0.2 mg/L. (Crawford and Lewis, 2005).

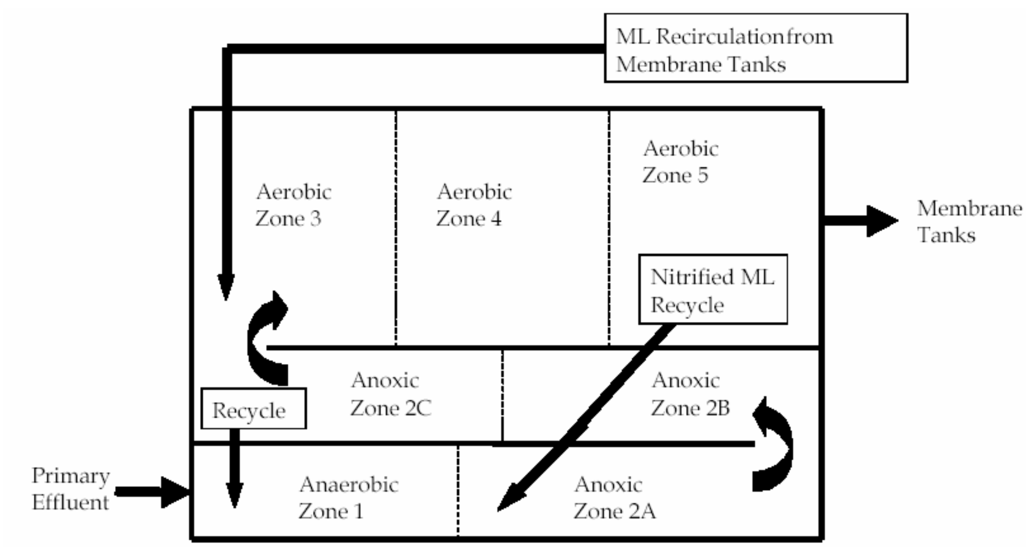

Figure 7: Traverse City Biological Process (Crawford and Lewis, 2005)

Industrial Treatment

MBR technology is also well suited for the treatment of industrial wastes. Most industrial wastes are high strength and nutrient limited, which generally leads to poor settling biomass, making the use of membranes ideal. Industrial applications for reuse are quite common and rely on membrane systems to provide high quality recycled process water. Industrial plants commonly consume more than a million gallons of potable water per day as process water. Reduction of industrial consumption through reuse can have a major impact on local environments and water availabilities.

Scott and Smith (1996) studied the application of an MBR system for the treatment of ice-cream production waste. Despite a higher initial cost, a 0.2 μm ceramic membrane was used due increased longevity and previous experience in industrial applications. The ceramic membrane was used for both filtration and aeration. The waste stream contained COD levels between 8000 – 10000 mg/L and BOD levels between 2000 – 4000 mg/L at a temperature of 22 - 32°C. The waste stream had a BOD_5:N:P ratio of 1000:1:5 (compared to an ideal conventional treatment ratio of 100:1:5). COD removals ranged between 83 and 97%, and BOD removals ranged between 90 and 98% depending on the system configuration. Another advantage of the MBR system was the ability of the system to maintain a stable pH of 6 – 8, even at feed concentrations over 10. This was attributed to the presence of lactic acid bacteria.

Murray et al. (2005) presented the application of MBR treatment to beverage manufacturing waste. The MBR process was chosen due to its ability to treat a highly variable, high temperature high strength waste, without the need for settling. The limited space available and the high quality water for reuse made MBR the ideal choice. The bottling wastewater had an abnormal nutrient profile high in H, O, and S (Figure 8). The regulation of nutrients within the MBR had a large effect on process performance. Upon start-up the system had a flux rate of 26 gal/ft^2d and required cleaning every 2 – 7 days. Adjustment of the nutrient deficiency improved the flux rate to 53 gal/ft^2d and reduced cleaning requirements to once every 30 days. A C:N:P ratio of 100:10:2 was found to provide the best results.

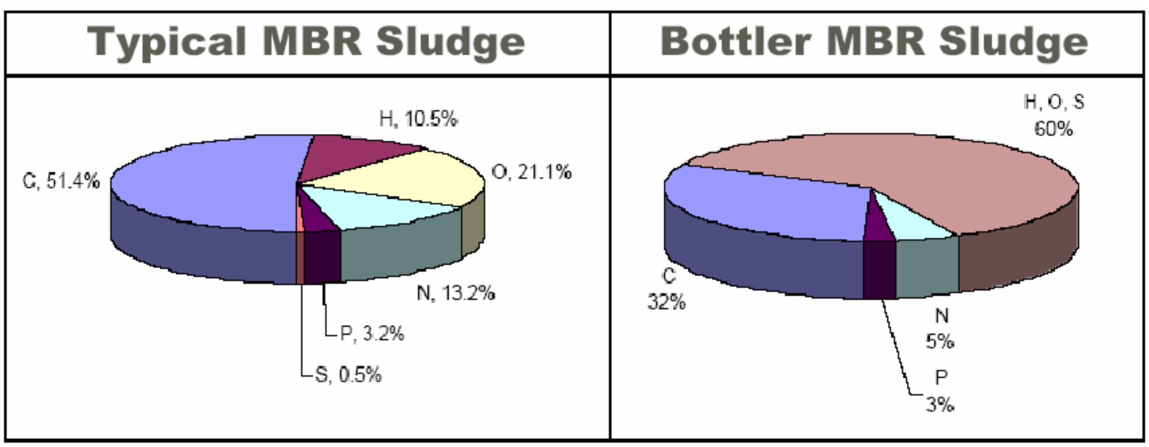

Figure 8: Comparison of Typical and Bottling Sludge Nutrient Profiles (Murray et al., 2005)

Water Reclamation

The use of MBR technology for reclamation is a rapidly expanding application. MBR technology is well suited for reuse treatment due to its small footprint and relatively easy operation. Small MBR systems can be designed to pull wastewater directly from the sewer at the remote points of reuse, eliminating the need for large central treatment plants and redistribution. MBR effluent is ideal for further treatment by reverse osmosis. The high quality of the MBR permeate allows increased RO flux with reduced fouling. Following RO treatment the water generally meets or exceeds all drinking water standards and may be even higher in quality than “virgin” water. Despite the high water quality public acceptance within the US is difficult. Studies have suggested that a hierarchy of acceptable use exists (Howell, 2004).

Treatment Reuse Hierarchy:

1. Forest Irrigation
2. Forage Crop Irrigation
3. Food Crop Irrigation
4. Park and Garden Irrigation
5. Livestock Watering
6. Cooling
7. Industrial Cleaning
8. Industrial Process
9. Fishery Use
10. Recreational Water Supplies
11. Public Grey Water
12. Public Drinking Water

In many cases the publics fears are unfounded or irrational as “de-facto” reuse of drinking water supplies occurs already, often with less treatment than direct reuse designed systems. In areas with ample water supplies the reuse of economic cost of wastewater reuse cannot usually be justified. In areas with water scarcity such as Singapore, which relies on Malaysia to supply it’s water the reuse of water is highly accepted. Reused water is sold under the name NeWater and all wastewater treatment plants are being retrofitted with MF, RO and UV systems for production (Layson, 2004).

MBR Manufacturers and Full Scale Plants

Within the US three main manufacturers market an MBR system. These include Zenon, USFilter, and Kubota which is distributed by Enviroquip. Each system is unique in its design and provides making it almost impossible to interchange systems within the design process.

Zenon

Zenon Environmental Inc. is headquartered in Canada and markets the ZeeWeed MBR system. Zenon is a membrane only manufacturer that has become the industry leader in MBR. The ZeeWeed system uses reinforced hollow fiber membranes immersed directly in the aeration basin. Zenon membranes are arranged in rectangular modules which form a cassette (Figure 9). Coarse aeration at the bottom of the membranes helps keep them clean. Permeate is drawn from the system by a vacuum pump. Zenon has full scale plants operating in Traverse City, MI, American Canyon, CA and Fulton County, GA. An MBR plant schematic is shown in Figure 10.

Figure 9: Zenon Laminated Hollow Fiber Membranes (www.zenon.com)

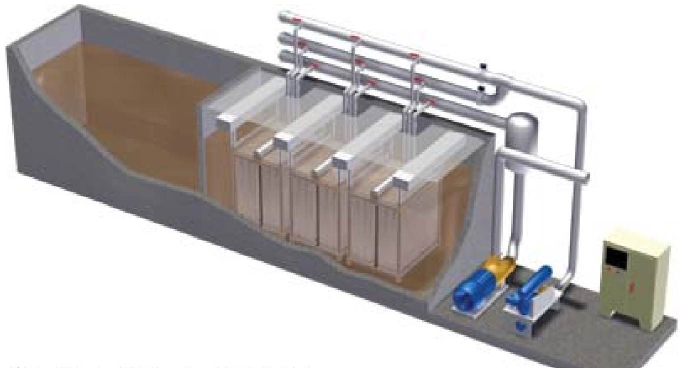

Figure 10: Zenon MBR Plant (www.zenon.com)

USFilter

USFilter is the largest environmental treatment company in the United States. MBR systems are manufactured and sold by the Memcor division located in Ames, Iowa. Although USFilter has recently entered the MBR market they are trying to make up for lost time. The Memcor Memjet MBR system uses hollow fiber membranes arranged in round modules on racks submerged in a separate membrane basin (Figure 11). Aeration and mixed liquor is introduced together through a two-phase air-water jet located at the bottom of the module. This Memjet system creates an even distribution of MLSS across the module and helps scour deposited solids from the membrane surface. USFilter also offers an MBR package plant called the FastPac MBR that is fully self contained for small scale systems (Figure 12). USFilter has full scale MBR plants operating in Crescent City, CA, Newhall Ranch, CA, and Everglades National Park, FL.

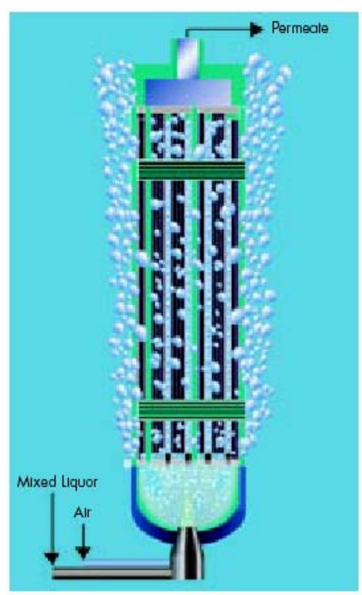

Figure 11: USFilter Hollow Fiber Membrane Module Rack and Memjet System (www.usfilter.com)

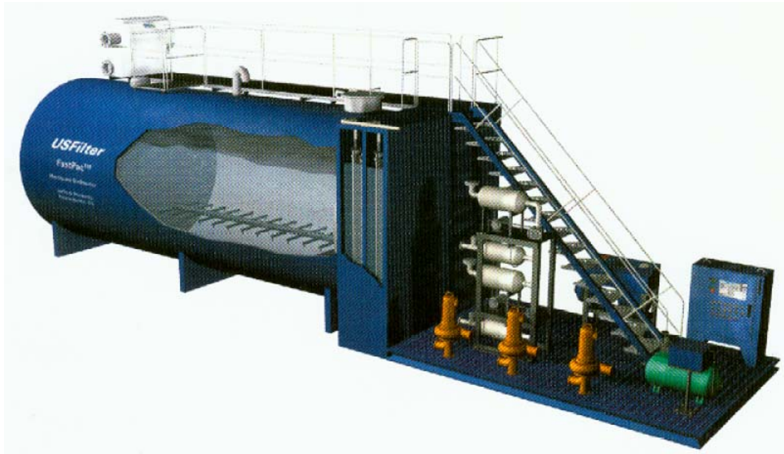

Figure 12: USFilter FastPac MBR (www.usfilter.com)

Kubota

Kubota membranes are distributed within the U.S. by Enviroquip Inc. The system utilizes flat plate membranes loaded within multiple cassettes in a plug flow basin. The membrane cassettes are installed directly in the aeration basin (Figure 13). Kubota has package scale MBR plants operating in Running Springs, CA, Tulalip, WA, and McKinney Roughs, TX.

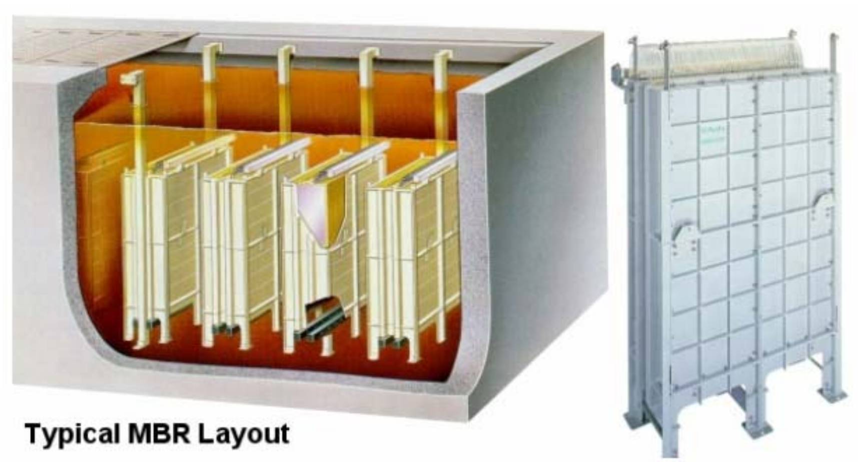

Figure 13: Kubota Plate and Frame MBR Configuration (www.enviroquip.com)

Conclusion

The application of MBR technology is rapidly expanding, with new installation occurring every year. MBR technology is highly suited for the reclamation of waste water due to the ability to produce drinking water quality effluent. The effluent produced can be reused within industrial processes or discharged to surface waters without degrading streams and rivers. The small foot print and ease of operation of the MBR systems makes it ideal for application in remote areas where wastewater can be reused for irrigation or ground water recharge. In addition MBR can be adapted to almost any industrial or municipal wastewater, reducing demand on local water supplies, and pollution in local water bodies.

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