Preliminary Technology Review: Membrane Wastewater Treatment

1. Introduction

EPA reviewed information on membrane treatment of wastewater from previous effluent limitations, guidelines, and standards (ELGs) and EPA's Industrial Wastewater Treatment Technology (IWTT, https://www.epa.gov/eg/industrial-wastewater-treatment-technology-database-iwtt) database as of August 2021 to summarize the status in industrial applications, provide an overview of the technology for use in industry studies, and characterize treatment capabilities. Section 2 includes an overview of membrane wastewater treatment and treatment capabilities. Section 3 describes considerations for evaluating this technology as part of an industry study or rulemaking. Section 4 presents references.

2. Technology Overview

A membrane is a barrier that allows certain substances to pass through while blocking others. In wastewater treatment applications, membranes allow water to pass through while preventing unwanted substances from passing through with the water. This occurs when a driving force is applied, such as a pressure differential. Molecules and particles smaller than the pore size, the spaces or voids in the membrane, pass through the membrane to the opposite side while larger matter builds up in a cake layer on the membrane surface. Accumulated material on the membrane surface must be cleaned to maintain membrane performance.

Depending on the pore size and membrane configuration, membranes can be used to treat total suspended solids (TSS), total dissolved solids (TDS), oil and grease, microbes, natural organic matter, and minerals. Key streams generated by membrane treatment include:

- **Permeate** - The treated wastewater stream produced by membrane treatment. This is the water that passes through the membrane pores.
- **Concentrate** – The material that does not pass through the membrane. This can also be referred to as reject. Portions of this stream can be recirculated back to the inlet of the membrane for further treatment, further treated by other technologies, or disposed.
- **Wastewater generated from cleaning operations** – This includes spent cleaning chemicals and material built up on the surface of the membrane.

Membrane systems are often characterized by their percent recovery, which refers to the amount of influent that will be recovered as permeate. This value will vary based on the characteristics of the water being treated and the membrane but is useful to determine the amount of concentrate that will need to be managed. For example, a membrane system with 80 percent recovery that treats a 100 gallon per minute flow will generate in 80 gallons per minute of permeate and 20 gallons per minute of concentrate.

Disposal options for the concentrate stream will depend on the volume and characteristics Potential concentrate management options include:

- Deep-well Injection – Sequestering the concentrate stream deep underground, below drinking water aquifers. This disposal option can be used for smaller amounts of wastewater and depends on wastewater characteristics and the proximity to a well that is able to accept the wastewater.
- Evaporation Pond(s) – Using ponds to evaporate water and isolate solids. This type of disposal option is best suited for plants located in arid climates with a large amount of land available.
- Land Application – Applying the waste stream to soil surfaces. This type of disposal can be limited to those locations near land willing to accept the wastewater.
- Offsite Waste Management – Sending the stream to a centralized waste treatment (CWT) facility, publicly owned treatment works (POTW), or offsite disposal contractor.
- Additional wastewater treatment - Using additional treatment technologies to achieve further reduction in volume or eliminating the water and generating a solid stream. This could include using evaporation/crystallization or other thermal technologies operated to remove all or part of the liquid portion of the stream or filter presses where solids are disposed, and liquid is recycled.

Fouling is the general term for substances present in the wastewater absorbing or depositing on the surface of the membrane. The substances can be inorganic material such as salts, organic matter like fats, oils, or greases, or biofouling from the formation of biofilms on the membrane surface. A declining in the flow through the membrane or an increase in the driving force required to maintain the flow can indicate the need for membrane cleaning and eventually decreases the lifespan of the membrane. Membranes can be cleaned using chemicals or injecting air in the inlet water to create a turbulent environment to flush fouling substances off the membrane surface. Chemical cleaning solutions are generally acidic in nature but can vary based on the membrane material and wastewater characteristics. Spent cleaning wastewater can require neutralization prior to disposal. Depending on the characteristics, spent cleaning wastewater can be combined with membrane concentrate for disposal.

Even with regular cleaning, membranes can still degrade over time. Pores can become clogged, or cleaning operations are unable to clean all the fouling material. Pressure drop across a membrane is regularly monitored as an indicator of when membrane cleaning or replacement is needed. As the pressure drop across the membrane increases, it is becoming more and more difficult for water to pass through the membrane. If cleaning is unable to reduce the drop in pressure it may signal a need to replace the membrane. Studies of membrane life based on membrane replacements suggest a life of approximately eight years, with ceramic membranes expected to last longer (Judd, 2018). However, the timing of cleaning and life of a membrane will vary based on many factors including influent wastewater characteristics, operating pressures, and membrane configuration.

Membrane processes are often distinguished by the pore size and/or the process by which they affect separation. The most common membrane processes used for treatment of industrial wastewater are:

- Microfiltration
- Ultrafiltration
- Nanofiltration
- Reverse osmosis

Microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) use pressure to help force water through a semi-permeable membrane. Separation occurs based on the size of the pores as the water is pushed through. Reverse osmosis (RO) also uses pressure, but typically a much higher pressure than MF, UF, or NF, and relies on principles of osmosis. Osmosis occurs when a semi-permeable membrane separates two salt solutions of different concentrations. The water will migrate from the weaker solution to the stronger solution, until the two solutions are of the same concentration, because the semi-permeable membrane allows the water to pass through, but not the salt. In reverse osmosis, the two solutions are still separated by a semi-permeable membrane, but pressure is applied to reverse the natural flow of the water. This forces the water to move from the more concentrated solution to the weaker. The contaminants end up on one side of the semi-permeable membrane and the treated water is on the other side. Table 1 compares the most common membrane processes used for industrial wastewater treatment.

Table 1. Membrane Process Comparison

Process	Pore Size	Typical Operating Pressure	Pollutants Removed	Notes
MF	0.1 – 10 µm	< 50 psi	• Suspended solids • Macromolecules • Colloids • Bacteria	• Can be used as stand-alone treatment or prior to RO to reduce system size and fouling potential.
UF	0.001 – 0.1 µm	< 50 psi	• Suspended solids • Proteins • Fatty acids • Pathogens, viruses • Silica	• Can be used as stand-alone treatment or prior to RO to reduce system size and fouling potential.
NF	1-10 nm	50 – 150 psi	• Calcium • Heavy metals • Salts • Dissolved organics	• The basic design guidelines, operational parameters, and process considerations for NF and RO are similar.
RO	<1 nm	125 – 1,200 psi[a]	• Monovalent atoms (e.g., chlorine) • Heavy metals • Trace phosphates • Dissolved organics	• Cost of RO is typically high due to the energy costs of supplying a pressure for filtration to occur. Operating at lower pressures will reduce costs but can reduce removal efficiency.

Abbreviations – micrometers (µm), nanometers (nm)

a – RO systems can be categorized into three different subgroups, low-pressure systems which operate between 125 and 300 psi, standard systems which operate between 350 and 600 psi, and high-pressure systems which operate between 800 and 1,200 psi. High-pressure systems are typically used for seawater applications.

Membranes can be made of different types of materials including polymer-based films or ceramics. These membrane materials can be molded into different shapes (e.g., in a flat sheet or rolled into a tube) and configured in various ways. Membrane configuration, pore size, and membrane material of construction depend on the application, required treatment level, and characteristics of the water being treated. Common membrane configurations include:

- **Hollow fiber systems –** Uses several long, filaments or membrane tubes ranging from less than 1 to 3.5 millimeter in diameter in a PVC shell. As wastewater is pumped through each filament, particles too large to pass through remain inside. Because the filaments are so small, and packed so tightly together, scaling can easily develop as particles are deposited on the filaments or plug the small spaces between the filaments. Irreversible fouling and fiber breakage are the main problems with hollow fiber systems.

- **Plate and frame systems** – Uses membranes and spacers stacked together and held in place with a frame. Because this configuration includes spacers, the membranes are not packed as tightly together, and this configuration can be used for wastewater with higher solids content or higher viscosities since fluid can flow between the membranes without clogging/plugging issues. However, the addition of these spacers also requires a greater footprint than in other membrane configurations to accommodate the same membrane surface area.
- **Spiral-wound systems** – Uses a flat sheet membrane and spacer wrapped around a permeate collection tube to produce flow channels for permeate and feedwater. The feedwater is routed through these spacers, providing a space for water to flow between the membrane surfaces. The layers are wrapped concentrically around the inner tube creating the spiral shape. Water that reaches the center and flows into the inner tube is considered permeate. This design maximizes flow while minimizing the membrane module size. Due to the high packing density, TSS must be reduced to less than 5mg/L in the feed stream to prevent plugging of the membrane.
- **Tubular systems** – Uses several tube-like membranes, typically with a diameter of 2 millimeters or greater, placed within a pipe/shell. As the waste stream is passed through the tubes, it transfers the permeate to the pipe/shell side. These systems are much like hollow fiber systems, but with a lower packing density. The lower packing density allows for a more turbulent flow which can stir up particles that may otherwise scale or foul the membrane. This type of configuration can be used for hard-to-treat streams, such as those with high TDS, TSS, and oils, greases, and fats.

Recent developments in membrane technology have focused on water/wastewater reuse, fouling control, and nutrient control. The applications for membrane systems for wastewater treatment continues to expand and the cost for these systems is decreasing. Membrane systems are being developed to handle streams with higher solids content that have been typically considered too difficult for membranes to treat. Technologies that incorporate vibration, more systematic cleaning, and other methods to decrease fouling are emerging.

3. Considerations for Industry Studies

The versatility of membranes in treating wastewater along with lower costs have broadened their use in industrial treatment systems. More stringent water quality-based effluent limitations for direct dischargers have also contributed to examining new wastewater treatment options. Membranes are used by a variety of industries and can be used for treating the entire wastestream, or for sidestream treatment.

Membrane cleaning and membrane replacement can increase maintenance and operating costs and remain the limiting factor affecting the widespread application of membranes for industrial wastewater treatment.

3.1 Industrial Applications

Membranes are often combined with other chemical, physical, and biological wastewater treatment systems. Membrane filtration is part of the technology basis for BAT or PSES in one industrial point source category, Steam Electric Power Generating (CFR Part 423) (U.S. EPA, ELG Database).

Table 2 lists the regulated categories reporting the use of membrane filtration, as part of a treatment train, from EPA's IWTT database. Table 2 also lists the targeted pollutants for the full treatment train, as identified within IWTT, for papers associated with the industries presented.

Table 2. Regulated Industries Reporting the Use of Membrane Filtration Systems as Part of a Treatment Train in IWTT

Industrial Category	40 CFR Part	Targeted Pollutants for Full Treatment Train
Dairy Products Processing	405	Biochemical Oxygen Demand, Chemical Oxygen Demand, Fats, Total Dissolved Solids, Total Suspended Solids
Canned and Preserved Fruits and Vegetables Processing	407	Chemical Oxygen Demand, Total Dissolved Solids, Total Suspended Solids
Textile Mills	410	Solids
Concentrated Animal Feeding Operations (CAFOs)	412	Chemical Oxygen Demand, Nutrients, Total Suspended Solids
Organic Chemicals, Plastics and Synthetic Fibers (OCPSF)	414	Total Suspended Solids
Petroleum Refining	419	Biochemical Oxygen Demand, Chemical Oxygen Demand, Metals, Nutrients, Oil and Grease, Organics, Phenols, Solids, Total Dissolved Solids
Iron and Steel Manufacturing	420	Metals, Organics
Nonferrous Metals Manufacturing	421	Metals
Steam Electric Power Generating	423	Metals, Nutrients, Total Dissolved Solids, Total Suspended Solids
Ferroalloy Manufacturing	424	Cyanide, Metals, Nutrients, Sulfates, Total Dissolved Solids
Pulp, Paper and Paperboard	430	Biochemical Oxygen Demand, Chemical Oxygen Demand, Nutrients, Total Suspended Solids
Metal Finishing	433	Biochemical Oxygen Demand, Chemical Oxygen Demand, Metals, Nutrients, Oil and Grease, Organics, Solids
Coal Mining	434	Chemical Oxygen Demand, Metals, Nutrients, Organics, Total Dissolved Solids, Total Suspended Solids
Oil and Gas Extraction	435	Biochemical Oxygen Demand, Metals, Nutrients, Oil and Grease, Organics, Phenols, Solids
Mineral Mining and Processing	436	Metals, Nutrients, Organics, Total Dissolved Solids
Pharmaceutical Manufacturing	439	Total Suspended Solids
Transportation Equipment Cleaning	442	Biochemical Oxygen Demand, Chemical Oxygen Demand, Metals, Oil and Grease, Solids
Landfills	445	Biochemical Oxygen Demand, Chemical Oxygen Demand, Nutrients, Phenol, Thiocyanate
Airport Deicing	449	None identified.
Aluminum Forming	467	Biochemical Oxygen Demand, Chemical Oxygen Demand, Metals, Oil and Grease, Solids, Surfactants
Electrical and Electronic Components	469	Chemical Oxygen Demand, Metals, Nutrients, Solids

Table 2. Regulated Industries Reporting the Use of Membrane Filtration Systems as Part of a Treatment Train in IWTT

Industrial Category	40 CFR Part	Targeted Pollutants for Full Treatment Train
Miscellaneous Foods and Beverages	503	Total Suspended Solids
Independent and Stand Alone Labs	507	Metals

Source: U.S. EPA, IWTT.

Note: The targeted pollutants may not all be removed by membrane filtration alone. This table includes any treatment train where membrane filtration was noted, so additional treatment units may be included.

3.2 Applicability Considerations

As described Section 2, wastewater flowrate and characteristics will impact the membrane configuration and pore size. Membrane systems can be used in combination to achieve effective treatment (e.g., using MF or UF prior to RO to optimize RO performance). In all cases, the final destination of the permeate and concentrate streams should be considered when designing a membrane system.

3.3 Cost Considerations

Advances in membrane technology have resulted in lower costs, making membrane systems more viable from an economic standpoint. Membranes may also allow for the reuse of treated wastewater within production processes which decreases the volume discharged and required intake water volumes. System design and overall cost depend on the characteristics of the influent and the desired effluent quality. Costs for RO and NF treatment systems depend on the size of the system, which are impacted by wastewater flow rates and the level of pretreatment prior to membrane filtration. For example, if MF is used as pretreatment upstream of an RO system, the RO system can be smaller and less expensive. Concentrate disposal can be a large percentage of operation and maintenance (O&M) costs depending on the volume and method selected for disposal. Cost components include the following:

Capital Costs

- Purchased equipment
- Site preparation
- Engineering design fees
- Administrative/legal costs
- Inspections
- Contingencies
- Profits and overheads

Treatment system equipment for membrane treatment often includes the following:

- Tanks (equalization, permeate storage, concentrate storage)
- Membrane unit(s)
- Pumps
- Chemical cleaning equipment (tanks, pumps, storage)
- Pretreatment equipment
- Concentrate management equipment

Annual costs

- Chemicals (for cleaning)

- Energy requirements to run the treatment system
- Concentrate disposal
- Labor for operation and maintenance
- Maintenance materials

Membrane systems require routine maintenance for proper operation. Maintenance activities include:

- Membrane replacement.
- Membrane cleaning.
- Calibrating instrumentation and cleaning probes.
- Maintaining pumps (inspection, cleaning, lubrication, replacing seals and packing, replacing check valves, cleaning strainers).
- Monitoring tanks (inspection, cleaning, corrosion prevention).

3.4 Non-Water Quality Environmental Impacts

Non-water quality environmental impacts (NWEQI) from membrane treatment are higher for RO systems than MF or UF systems due to the increased pressure requirements. It can be difficult to compare NWQEI among different membrane systems because these impacts can depend heavily on the method of concentrate disposal (e.g., large energy requirements for thermal systems or large air emissions from hauling). Generally, systems with lower percent recoveries, where more concentrate is generated are also more likely to have higher NWQEI as this larger concentrate stream will need to be manage and disposed.

NWQEI for membrane treatment include:

- Energy required to pressurize the treatment system and pump wastewater.
- Energy requirements for concentrate disposal.
- Air emissions from treatment system and transportation.

4. References

1. U.S. EPA. Effluent Limitations Guidelines and Standards (ELG) Database. Available online at: https://owapps.epa.gov/elg/
2. U.S. EPA. Industrial Wastewater Treatment Technology Database (IWTT). Available online at: https://www.epa.gov/eg/industrial-wastewater-treatment-technology-database-iwtt
3. Judd, Simon. (2020). Membrane ageing – factors determining membrane replacement. Available online at: https://www.thembrsite.com/blog/membrane-ageing-factors-determining-membrane-replacement/.