

# APPLICATIONS OF MEMBRANE TECHNOLOGY IN WASTEWATER TREATMENT

Presented by-

**Rishika Singh (B-tech Chemical Engineering F.Y.)**

**Rutesh Vharamble (B-tech Chemical Engineering F.Y.)**

Department of Chemical Engineering

Dr. D. Y. Patil College of Engineering and Technology

## ABSTRACT

This paper aims to explore the role of membrane technology in various sectors of human lifestyle. Membrane technology solves major problems that we encounter often in our daily tasks, it might range from purification of the portable water to our medical use in kidney failure, Additionally, the study seeks to contextualize these applications within the broader landscape of membrane-based processes in industrial and municipal systems. The paper is structured in such a way that the readers find it easy to classify the different processes of membrane usage and how they complement their respective applications, an overview of membrane classification and key filtration mechanisms is presented; this is followed by an in-depth discussion of the applications and performance criteria. Subsequently, challenges and future directions in membrane technology are suggested, emphasizing the structural advancement in the existing technology to serve the societal purposes under most favourable conditions for continued innovation across all sectors of application.

## INTRODUCTION

Membrane technology, once confined to niche biomedical applications such as kidney dialysis, has now become a game-changer across multiple domains, including municipal water purification, industrial effluent treatment, and even household filtration systems. Its ability to separate and retain particles at the molecular or even ionic level—combined with compact design and scalability—has revolutionized how we think about filtration. From reclaiming potable water in arid regions to removing trace pharmaceuticals from sewage, the versatility of membrane processes like reverse osmosis, ultrafiltration, and nanofiltration cannot be overstated.

Moreover, as environmental regulations grow more stringent and society becomes more conscious of sustainability, the demand for energy-efficient, high-performance treatment systems continues to rise. Membrane technology meets this demand head-on, especially with the development of next-generation solutions like forward osmosis, electrodialysis, and mixed matrix membranes. These innovations are not only more effective but also reduce operational costs, minimize energy use, and offer modular designs suitable for both centralized and decentralized systems.

This paper aims to explore and evaluate the vast landscape of membrane technologies and their transformative role in wastewater treatment. It delves into the classification, operational mechanisms, and performance metrics of various membrane systems, while also highlighting key challenges and future directions. The goal is to provide a comprehensive understanding of how membrane-based treatment is shaping the future of water management, and how ongoing innovations could help tackle existing problems with more advanced and structured way of looking at new innovations which are more efficient and suitable.

# LITERATURE SURVEY

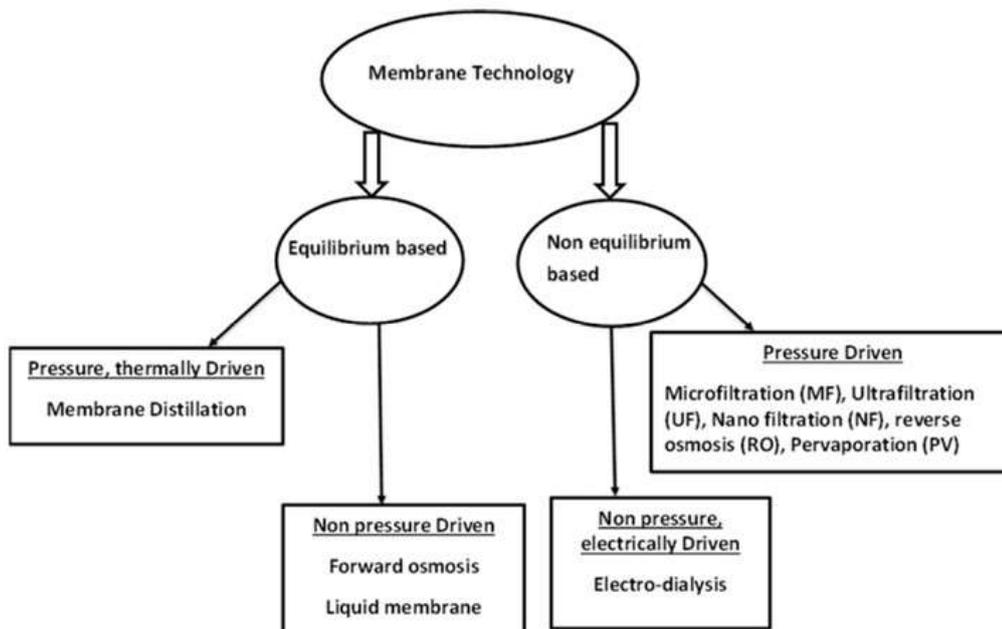
## I. TYPES OF MEMBRANE

### Based on Pore Size

Ronco, C., et al. (2006). "Membrane-Based Dialysis: From Conventional to Advanced Therapies." *Kidney International Supplements*, 70(103), S146–S151. Based on pore size and separation mechanism, membranes are also categorized into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). MF and UF are often used for removing suspended solids and macromolecules, while NF and RO are employed for fine separations, including the removal of salts, organics, and low-molecular-weight solutes. In medical dialysis, membranes used are functionally close to UF, designed to selectively allow the passage of urea, creatinine, and other metabolic wastes while retaining essential proteins and cells.

### Based on process type

#### 2.1. Pressure Driven Membrane Processes



Elorm Obotey Ezugbe, and Sudesh Rathilal

Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Durban 4000, South Africa;

The above-mentioned membrane types are governed by the pressure-driven principle.

**Microfiltration (MF):** Utilized for removing suspended solids, bacteria, and large colloids. It operates at low pressures (0.1–2 bar) and is often used as a pre-treatment step or disinfection system. These membranes are effective in removing suspended solids, turbidity, large colloids, and microorganisms such as bacteria and protozoa. The separation mechanism in MF is primarily **sieving**, where particles larger than the pore size are physically retained on the membrane surface.

Van der Bruggen, "A Review of Pressure-Driven Membrane Processes in Wastewater Treatment and Drinking Water Production." *Environmental Progress*

**Ultrafiltration (UF):** Removes viruses, macromolecules, and some organic matter, functioning at 1–5 bar. They can retain viruses, proteins, and macromolecular organics while allowing salts and low-molecular-weight solutes to pass through. The working principle involves both sieving and adsorptive interactions, making UF suitable for applications such as water reuse, food and beverage processing, and as a replacement for conventional coagulation-filtration systems.

UF is widely applied in municipal wastewater reuse and industrial effluent polishing.

*Madaeni, S. S. (1999). "The Application of Membrane Technology for Water Disinfection."*

**Nanofiltration (NF):** Operates at moderate pressures (4–30 bar) and can remove divalent salts, small organic molecules, and pesticides. The separation mechanism is a combination of **size exclusion** and **electrostatic interactions**, often governed by the Donnan effect, where membrane surface charge plays a role in ion rejection. NF is frequently applied in softening, dye removal, and partial desalination. It serves both industrial wastewater reclamation and tertiary municipal treatment.

*Van der Bruggen, B., et al. (2003). "A Review of Pressure-Driven Membrane Processes in Wastewater Treatment and Drinking Water Production." Environmental Progress*

*Hilal, N., et al. (2004). "Nanofiltration in Wastewater Treatment: Recent Developments and Future Prospects." Desalination*

**Reverse Osmosis (RO):** Employs high pressures (30–80 bar) and is capable of rejecting virtually all dissolved salts and organics. RO membranes are essentially non-porous, relying on **solution-diffusion** as the separation mechanism. Water molecules dissolve into the membrane matrix and diffuse across under high pressure (30–80 bar), leaving contaminants behind. RO is widely used in seawater desalination, ultrapure water production, and advanced wastewater treatment.

*Greenlee, L. F., et al. (2009). "Reverse Osmosis Desalination: Water Sources, Technology, and Today's Challenges."*

*Elorm Obotey Ezugbe, and Sudesh Rathilal*

*Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Durban 4000, South Africa;*

Among the pressure driven membrane processes, RO is highly known for its efficiency in separating small particles including bacteria and monovalent ions like sodium ions and chloride ions up to 99.5%. RO has been at the forefront of water reclamation through wastewater treatment and desalination of seawater for a long time. During reverse osmosis, a hydrostatic pressure is generated that is strong enough to overcome the intrinsic osmotic pressure of the feed. This is against the natural osmosis process. For the complete process, water molecules are absorbed onto the membrane surface (under pressure). These molecules diffuse through the membrane material and finally desorb at the permeate side of the membrane for collection.

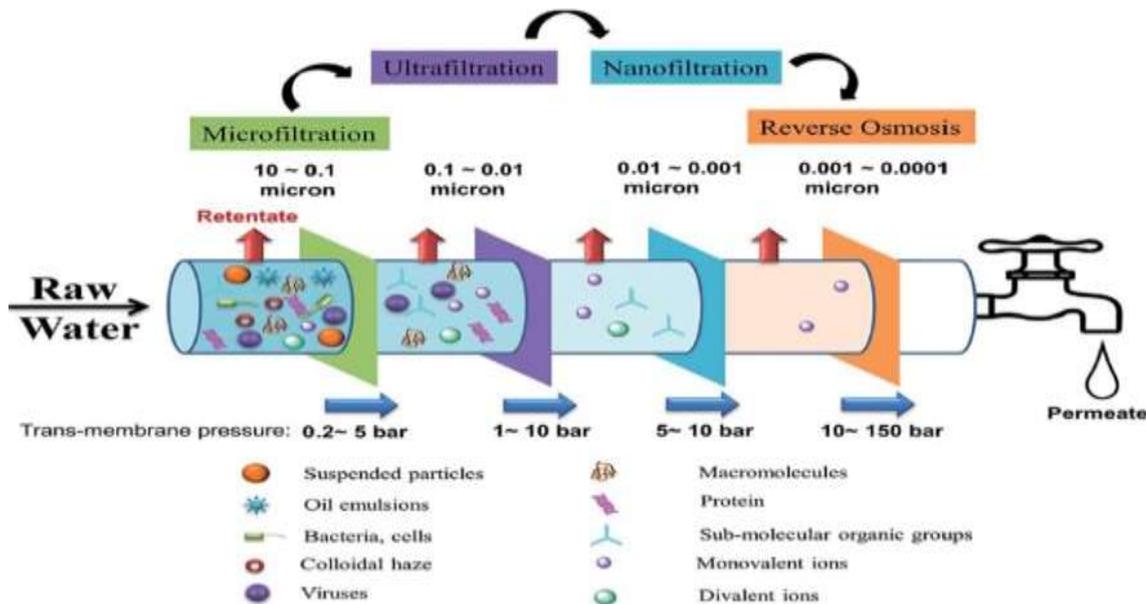
Membrane Process	* MWCO (kilo Dalton)	Retained Diameters (µm)	Pressure Required (bar)	Membrane Type	Average Permeability (l/m <sup>2</sup> h bar)	Solutes Retained
MF	100-500	10 <sup>-1</sup> -10	1-3	Porous, asymmetric or symmetric	500	Bacteria, fat, oil, grease, colloids, organics, micro-particles
UF	20-150	10 <sup>-3</sup> -1	2-5	Micro porous, asymmetric	150	Proteins, pigments, oils, sugar, organics, microplastics
NF	2-20	10 <sup>-3</sup> -10 <sup>-2</sup>	5-15	tight porous, asymmetric, thin film composite	10-20	Pigments, sulfates, divalent cations, divalent anions, lactose, sucrose, sodium chloride
RO	0.2-2	10 <sup>-4</sup> -10 <sup>-3</sup>	15-75	Semi porous, asymmetric, thin film composite	5-10	All contaminants including monovalent ions

\* MWCO = Molecular weight cut off.

## Mechanism of pressure- driven operation

Mulder, M. (1996). *Basic Principles of Membrane Technology*. Springer Science & Business Media.

In pressure-driven membrane systems, water is forced through a membrane with specific pore size or dense structure, depending on the desired separation. The driving force is the applied pressure gradient, which must exceed the osmotic pressure of the feed solution. The degree of separation is primarily governed by the membrane's structure and surface properties. Membranes may operate in dead-end or cross-flow modes, with the latter offering enhanced fouling control and higher flux stability



RSC Adv., 2018, 8, 37915-37938 | 37917

This journal is © The Royal Society of Chemistry 2018

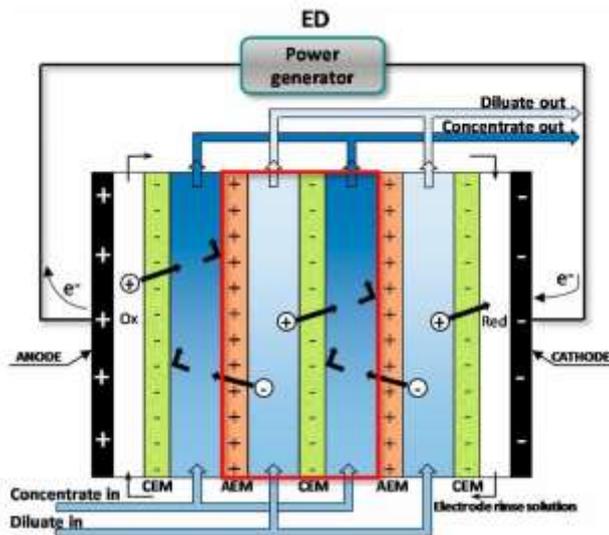
## 2.2 Non-Pressure Driven/ diffusion

### Forward Osmosis Techniques

Forward Osmosis (FO) is a membrane-based water treatment technology driven by osmotic pressure differences between two solutions. FO relies on the natural osmotic pressure gradient to move water across a semi-permeable membrane from a feed solution (low solute concentration) to a draw solution (high solute concentration). Unlike Reverse Osmosis (RO), which uses hydraulic pressure to counteract osmotic pressure, FO achieves separation without requiring high-pressure pumps, leading to lower energy consumption.

A semi-permeable membrane separates the feed solution and draw solution. Water flows naturally from the feed side to the draw side due to the osmotic gradient. The draw solution becomes diluted as water permeates through the membrane, while the feed solution becomes concentrated. The diluted draw solution is re-concentrated for reuse, often using thermal, Hybrid (FO-NF, FO-MBR, FOMD), or RO processes. Lower energy requirements compared to RO due to the absence of high-pressure pumps.

## 2.3 Electrically driven osmosis



**Electrodialysis (ED)** is an electrically driven membrane separation process widely used in wastewater treatment, desalination, and chemical recovery. It operates by applying a direct current (DC) electric field across a stack of alternating ionexchange membranes — specifically, cation-exchange membranes (CEMs) and anion-exchange membranes (AEMs) — placed between two electrodes (anode and cathode). These membranes are selectively permeable: CEMs allow only positively charged ions (cations) to pass through, while AEMs permit only negatively charged ions (anions). When an electric current is applied, cations migrate toward the cathode and pass through the CEM but are blocked by the adjacent AEM, while anions move toward the anode and pass through the AEM but are stopped by the CEM. As a result, ions are continuously removed from certain compartments (called diluate compartments), leading to desalinated or purified water, while accumulating in other compartments (concentrate compartments), forming a concentrated brine. This process is particularly efficient for low to moderate salinity streams, such as brackish water or certain industrial effluents.

Electrodialysis is known for its high ion selectivity, relatively low energy consumption (especially compared to pressure-driven systems like reverse osmosis), and the ability to recover valuable salts or chemicals from wastewater. It finds applications not only in municipal and industrial water treatment but also in the food and pharmaceutical industries — for example, in the demineralization of whey or sugar solutions. However, its performance can be affected by membrane fouling and scaling, and it is not suitable for removing non-ionic pollutants. Despite these limitations, ongoing research and innovations such as bipolar membranes and electro dialysis reversal (EDR) are enhancing its efficiency and expanding its range of applications.

Electrodialysis is known for its high ion selectivity, relatively low energy consumption (especially compared to pressure-driven systems like reverse osmosis), and the ability to recover valuable salts or chemicals from wastewater. It finds applications not only in municipal and industrial water treatment but also in the food and pharmaceutical industries — for example, in the demineralization of whey or sugar solutions. However, its performance can be affected by membrane fouling and scaling, and it is not suitable for removing non-ionic pollutants. Despite these limitations, ongoing research and innovations such as bipolar membranes and electro dialysis reversal (EDR) are enhancing its efficiency and expanding its range of applications.

*Strathmann, H. (2010). Electrodialysis, a mature technology with a multitude of new applications. Desalination*

## II. APPLICATIONS OF MEMBRANE TECHNOLOGY

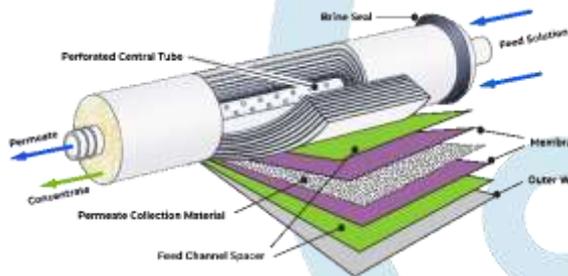
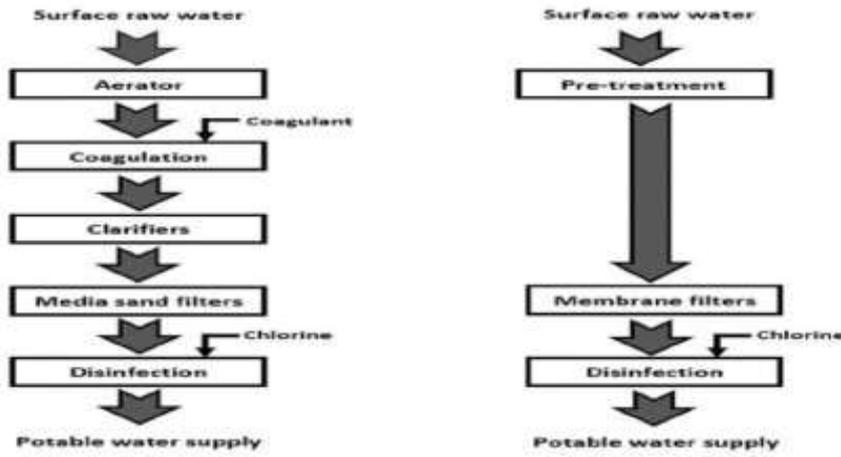
In **household applications**, membranes are widely used in domestic water purification units, such as reverse osmosis filters, to ensure safe drinking water. **Municipal sectors** implement membrane processes like ultrafiltration and nanofiltration in wastewater treatment and water recycling systems, contributing to sustainable urban water management. In the **medical field**, membrane technologies are critical in haemodialysis, drug delivery systems, and sterile filtration, enabling life-saving treatments and high-purity solutions. **Industrial applications** range from food and beverage processing, such as juice clarification and dairy concentration, to chemical manufacturing and oil–water separation.

### Applications of membrane technology in drinking water treatment

Generations of drinking wastewater treatment

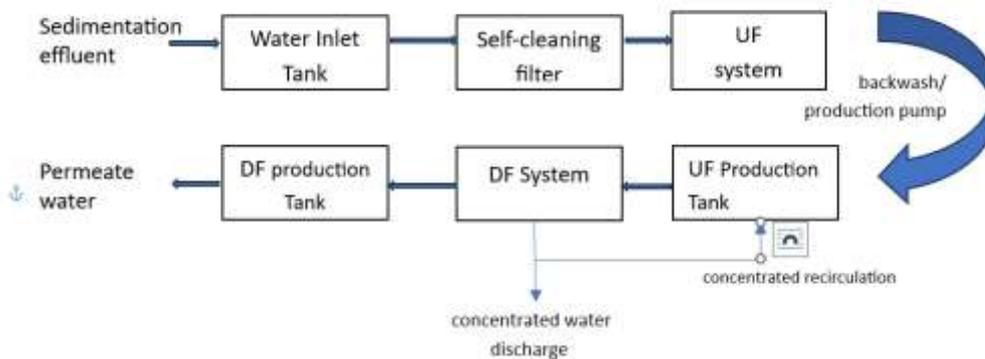
- 1<sup>st</sup> generation: Coagulation- Precipitation-Filtration-disinfection (removal of suspended solid particles, colloidal particle, plant organic, bacteria and virus.
- 2<sup>nd</sup> generation- Coagulation- Precipitation-Filtration-Ozone activated carbon- disinfection (removal of odour, colour, pesticides etc.)
- 3<sup>rd</sup> generation- Coagulation- Precipitation- Membrane Filtration-(UF) Disinfection

d. 4<sup>th</sup> generation- - Coagulation- Precipitation- Membrane Filtration-(NF) Disinfection



In household reverse osmosis (RO) systems, water purification involves several stages centered around a semi-permeable membrane. Initially, water passes through a sediment filter to remove particles like sand and rust, followed by an activated carbon filter that removes chlorine and organic compounds. The pre-treated water is then

forced under pressure (40–100 psi) through the RO membrane, which has pore sizes around 0.0001 microns. This membrane allows only water molecules to pass, rejecting up to 99% of dissolved salts, heavy metals, bacteria, and viruses. The purified water then flows through a post-carbon filter to improve taste and is stored in a pressurized tank. Wastewater containing concentrated contaminants is discharged via a reject line. Some systems also include UV, mineralization, or TDS control stages to enhance water quality.



### Application of membrane in Haemodialysis

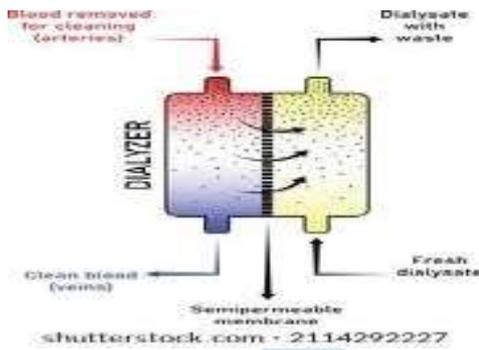
Clark, W. R. (2005). *The Membrane in Haemodialysis: A Primer. Dialysis & Transplantation*

Van der Bruggen, B., Vandecasteele, C., et al. (2003). *Review: A review of pressure-driven membrane processes in wastewater treatment and drinking water production. Environmental Progress*

Haemodialysis utilizes a semipermeable membrane to separate waste products and excess fluids from the blood. Blood flows on one side of the membrane, while a specially formulated fluid called dialysate flows on the other side. Due to concentration gradients, small solutes like urea, creatinine, and electrolytes diffuse across the membrane into the dialysate, while larger components such as blood cells and proteins are retained. The process is governed by Diffusion: Solute moves from high to low concentration Ultrafiltration: Fluid moves across the membrane under a pressure gradient and Osmosis: Helps balance solute concentration across the membrane.

This selective separation is analogous to membrane processes used in wastewater treatment such as reverse osmosis (RO) and ultrafiltration (UF), where unwanted contaminants are removed based on size exclusion or charge-based separation.

Dialysis membranes are often made of synthetic polymers such as Poly sulfone or polyether sulfone. These materials offer high biocompatibility, stability, and performance. The hollow fibre module configuration is most used, where blood passes through thousands of fine fibres and dialysate flows outside the fibres in a countercurrent direction, maximizing surface area for exchange. Similar hollow fibre membranes are used in membrane bioreactors (MBRs) in wastewater treatment to provide high-efficiency filtration of organic and microbial contaminants.



### Application of membrane technology industrial Municipal Wastewater treatment

*etch2o.com*

*WPADMIN / April 14, 2023 / Wastewater Treatment, Water & Wastewater Solutions*

In municipal and industrial sectors, MBRs offer superior treatment performance, compact design, and the ability to produce high-quality effluents that meet stringent discharge standards. In municipal applications, MBRs outperform conventional activated sludge systems by efficiently removing suspended solids, organic matter, nutrients, bacteria, and viruses. Industrial sectors, including food processing and paper manufacturing, utilize MBRs for their capacity to handle complex effluents with high contaminant loads.

The membrane component—typically ultrafiltration or microfiltration—acts as a physical barrier, ensuring the retention of biomass and pathogens while allowing clean water to pass. Innovations in membrane materials and AnMBR (anaerobic MBR) designs are enhancing system efficiency, reducing operational costs, and mitigating membrane fouling. As regulatory pressures and sustainability demands increase, MBR technology is poised for broader adoption across various wastewater treatment scenarios.

Application	Main Goal	Membrane Used	Challenge	Output Use
Municipal	Clean Water and Pathogen Removal	MBR (UF/MF), RO	High Volume, Moderate Strength	Discharge, reuse
Industrial	Contaminant-specific treatment	RO, NF, UF, ED	Complex, variable waste streams	Reuse, discharge, recovery
Sludge Treatment	Volume reduction, resource recovery	UF, FO, AnMBR	High Solids, fouling risk	Dewatered sludge, biogas

## FUTURE SCOPE OF MEMBRANE TECHNOLOGY

The choice of a membrane system should be based on feed water quality and its application purpose. While **Forward Osmosis (FO)** has emerged as a promising low-energy membrane process for wastewater treatment, its reliance on a subsequent **post-treatment stage**, typically using **Reverse Osmosis (RO)** or other polishing steps, limits its standalone application. The primary challenge lies in the incomplete separation of solutes and the need for draw solution regeneration, which introduces additional energy demands and infrastructure requirements. In this context, the integration of **Mixed Matrix Membranes (MMMs)** with FO offers a transformative approach to address these limitations. **MMMs**, which incorporate inorganic fillers (e.g., zeolites, metal-organic frameworks, graphene oxide) within a polymeric matrix, provide enhanced permeability, selectivity, and anti-fouling characteristics compared to traditional FO membranes. By incorporating MMMs as a secondary stage immediately after FO—either as a laminated layer or a physically separate but inline module—the system can achieve **high-efficiency solute rejection and direct water recovery** without the need for energy-intensive RO units.

Structurally, such a hybrid membrane system can be realized by either fabricating a **dual-layer membrane** where the FO active layer is followed by an MMM rejection layer or by **serially connecting FO and MMM modules** in a compact, modular skid. The MMM component can be tailored to target specific pollutants based on the nature of its fillers and surface chemistry, thus ensuring precise control over the final water quality. This integration not only reduces **energy consumption** by leveraging the passive osmotic gradient of FO and the enhanced selectivity of MMMs but also minimizes the **overall footprint** and **capital cost** of the treatment facility. Moreover, the improved antifouling behaviour of MMMs can reduce maintenance frequency and prolong membrane life, contributing to the system's economic and environmental sustainability. Such innovations position FO-MMM hybrid systems as **one-stop solutions** for decentralized or large-scale wastewater treatment, particularly in energy-constrained or space-limited environments.

### CONCLUSION

This study highlights how membrane technologies are evolving to meet the growing demand for efficient and sustainable wastewater treatment. While well-established methods like reverse osmosis (RO) and ultrafiltration (UF) remain widely used, newer approaches—such as forward osmosis and electrodialysis—are steadily gaining attention. Their appeal lies in their ability to treat water with less energy and through more selective, innovative separation processes.

One of the most exciting developments is the use of advanced materials like mixed matrix membranes, which help tackle persistent challenges like membrane fouling and high energy consumption. When these materials are combined into hybrid systems, they open new possibilities for more reliable and efficient water purification.

Looking ahead, it's clear that membrane-based systems have a vital role to play in shaping the future of water treatment. With ongoing research and thoughtful application, they could be key to ensuring access to clean water, supporting resource recovery, and building more resilient environmental systems in a world facing increasing water stress.