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Advancements in Membrane Technologies for Industrial Wastewater Treatment: Challenges, Benefits, and Future Directions

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Abstract:

Due to environmental and regulatory challenges, membrane separation technologies have become an essential part of treating industrial wastewater. The comprehensive capabilities and research in membrane technologies of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) for the textile, petrochemicals, and metal plating industries were reviewed by this paper. These technologies have various advantages, including high contaminant removal efficiency, resource recovery, and then subsequent water reuse, making a substantial contribution to sustainability and environmental protection. Nonetheless, persistent issues, especially membrane fouling, and relatively high energy consumption and capital expenditure still hinder their scalability deployment. The paper also outlines the latest advancements to address these challenges, such as anti-fouling membrane materials, hybrid membrane systems, and energy integration using renewable counterparts. Finally, future research is discussed in terms of (a) enhancing membrane stability, (b) reducing production costs, and (c) engineering for specific industry-related applications. Our results highlight the transformative power of membrane technologies to drive sustainable wastewater treatment and recover resources, marking them as a critical asset for enabling the circular economy.

Keywords: *Membrane technology, industrial wastewater treatment, microfiltration, ultrafiltration, nanofiltration, reverse osmosis, sustainability, resource recovery, membrane fouling.*

Introduction

Water is the most essential element in human life as well as necessary for industrial processes. Nevertheless, rapid industrialization has produced vast amounts of industrial wastewater streams that are subjecting complex and toxic pollutants like heavy metals, oils, dyes, and organics (Fu, & Wang, 2011). It is necessary to treat this wastewater properly since it can lead to severe environmental deterioration, water bodies contamination, aquatic ecosystems in danger, and health risks for human beings (Choudhury, et al., 2018).

The source of industrial wastewater is particular to the industry itself. Wastewater produced by various industries contains different types of chemicals; textile industries produce wastewater with high dye concentration, and the metal plating industry produces wastewater containing heavy metals (Marcucci, et al., 2001). Chemical coagulation, sedimentation, and biological processes have been the primary methods used to treat such effluents but are traditional wastewater treatment methods. However, such methods are generally inadequate against increasingly stringent environmental regulations to handle complex industrial wastewater (with affluents varying in composition) (Elimelech, & Phillip, 2011). What is worse, they are energy-consuming, produce a large amount of sludge, and need further post-treatment due to the generation of secondary pollutants (Judd, & Jefferson, 2003).

These challenges have consequently paved the way for new membrane separation technologies, which offer a robust solution for industrial wastewater treatment. These technologies rely on the relatively simple fact that membranes have selective permeability — enabling them to remove contaminants according to their size, charge, or other molecular properties. These technologies, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) processes, offer high treatment efficiency and consume lower energy and chemicals, which create an interest in the ground of membrane technology-based water purification process addressing the limitation of the conventional method described above (Marcucci, et al., 2001).

MF membranes have been increasingly used as a pretreatment process for the removal of suspended solids, bacteria, and larger particles in wastewater streams in many industries (van der Bruggen, Vandecasteele, & Lejon, 2003). Ultrafiltration (UF) membranes have pore sizes smaller than those of MF membranes. They are ideal for the separation of colloids, proteins, and organic macromolecules, paving a promising way to expand industrial applications in textiles, pulp, and paper (Zsirai, et al., 2016). Nanofiltration (NF) and reverse osmosis (RO) membranes have a high removal efficiency of dissolved salts, heavy metals, and organic pollutants, which offer an effective strategy for treating waste brine or resource recovery (Wang, et al., 2015).

However, these membrane technologies do not come without their hurdles. Membrane fouling is a matter of concern in MF as well, which will eventually reduce the permeability because of the cake layer formed in the membrane surface, thus resulting in high operational costs for cleaning and replacing membranes (Zsirai, et al., 2016). Furthermore, the initial high capital investment of membrane systems could inhibit specific industries from adopting this highly effective technology, minimal and medium-sized enterprises (Peiris, et al., 2010). Nevertheless, current research focusing on the material synthesis of novel membrane materials like ceramic membranes and nanocomposite ones can help in overcoming these challenges, offering potential solutions to make them sustainable in the long run (Anis, Hashaikeh, & Hilal, 2019).

Literature Review

Membrane Technologies for Wastewater Treatment

During the last decades, membrane separations have become a key technology in industrial wastewater treatment. These technologies hold a key unique advantage as they are able to separate specific contaminants (e.g., suspended solids, heavy metals, oils, and organic pollutants) from wastewater streams in the environment. The rapid increase in environmental awareness and increasing regulatory requirements for wastewater discharge have forced industries to install various membrane processes as a mandate unit operation in their wastewater treatment network (Zeman, & Zydney, 1996).

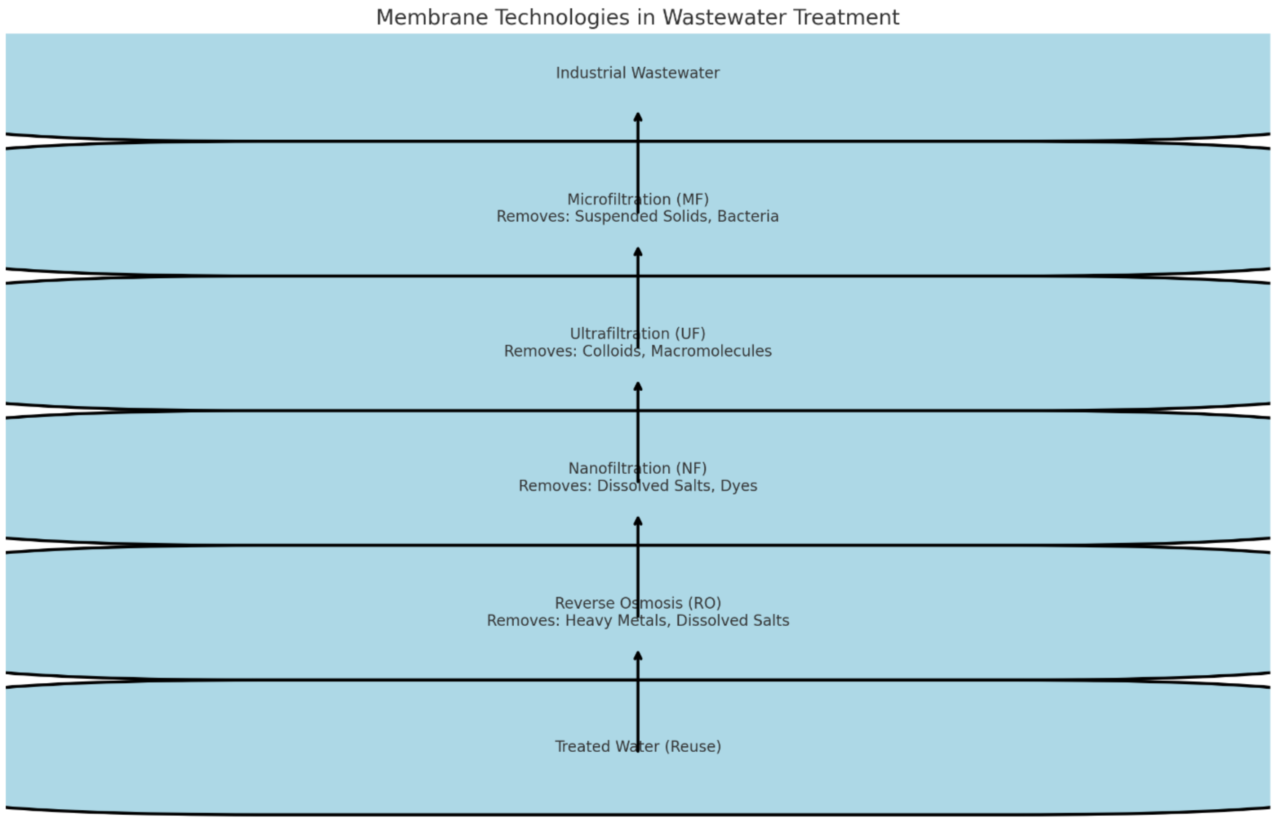

Figure 1. Flowchart of Membrane Technologies in Wastewater Treatment

MF has been used in some industrial wastewater systems as a pretreatment step due to its high removal efficiency of coarse particles and bacteria (Gerardi et al. Harif and Adin (2007) demonstrated the application of MF membranes for food and beverage effluent treatments, which led to the significant removal of suspended solids and organic pollutants, improving water quality (Zeman, & Zydney, 1996). Likewise, ultrafiltration (UF) has seen broad acceptance in industrial applications such as the textile and petrochemical industries, where UF is used to remove colloidal particles and macromolecules. A study conducted for the recovery of proteins and enzymes from food processing effluents proved to be effective in recovering value-added products to UF membranes (Bhattacharyya, & Ghosh, 2004).

Nanofiltration (NF) along with reverse osmosis (RO) technologies are widely used in industries dealing with ultra-contaminated discharge, i.e., textile and metal plating sectors. NF, unlike UF membranes with smaller pore sizes that allow the passage of dissolved salts and organic molecules, retained a high flux rate, according to Tang et al. In their work on TEOS/Fe (III) crossover particles (2009), NF membranes were effectively used for the treatment of the textile industry's dye-containing wastewater, resulting in higher than 90% removal of dyes alongside retaining essential water-soluble salts. The reverse osmosis process, in turn, is ideal for the treatment of high-salinity wastewater, such as desalination plant brines or effluents from chemical industries, according to Greenlee et al. As reported by Chadha and Bruni (2009), RO systems demonstrated high removal efficiency for dissolved ions and heavy metals in industrial effluents. Subsequently, they proved to be a practicable solution, making water reuse economically viable in water-scarce regions.

Benefits of Membrane Separation Technologies

Introduction Membrane separation technologies have proved their efficiency in industrial wastewater treatment. It has many advantages, among which the main one is that it offers high separation efficiency and hence industries get cleaner effluents meeting regulatory discharge standards. Membrane technologies can deliver in a single step what conventional treatment methods may need several steps to extract combined contaminants. This is very important in sectors of pharmaceuticals within which high-purity effluents are a must (Pérez-González, et al., 2012).

Furthermore, compared with conventional thermal separation process, membrane technologies require less energy. For instance, Elimelech and Phillip (2011) quote that reverse osmosis is seen as a more energy-efficient form of water desalination than evaporation or distillation processes. Additionally, membrane systems are designed to be space-efficient so that they can easily fit into any pre-existing industrial line without the need for massive capital expenditures on new lines. This makes membrane technologies especially attractive to industries that need to renovate or upgrade their existing wastewater treatment plants to meet the demands of new environmental regulations.

In addition, membrane processes allow the recovery of resources, which is an essential condition for sustainable water management. Membrane systems can also be applied in various industries for the recovery of valuable heavy metals such as zinc and copper from their wastewater streams (e.g., metal plating, etc.), leading to lower environmental impact while eliminating heavy metals-related operational costs (Mansouri, Harrisson, & Chen, 2010). There is also increasing use of UF and MF for protein recovery (among other valuable components) in the food and beverage industry, which can then be re-used in production processes (Cassano, Criscuoli, & Drioli, 2011).

Challenges and Limitations

Membrane fouling is the leading drawback of membrane technologies despite their many advantages. Such accumulation of contaminants on the membrane surface leads to a decrease in permeability over time, which is referred to as fouling by many researchers. It has an adverse effect on operating costs due to frequent cleaning or replacement of worn-out membranes (Madaeni, & Mohamamdi, 2010). However, fouling is particularly severe in applications with oil-laden waste from which oils are emulsified, and the greases can substantially reduce membrane efficiency (Koseoglu, et al., 2013).

Membrane technology is capital-intensive, and it is a severe limitation. Although membrane technologies are of lower operational cost in the long term, the initial capital costs for membrane materials, modules, and supporting facilities can be prohibitive, especially for small and medium-sized enterprises (Singh, & Hankins, 2012). Also, membrane materials' selectivity can restrict their use for the treatment of very diverse waste waters water in which different contaminants need different filtration mechanisms. Current research is aimed at creating more stable and flexible membrane materials (such as mixed-matrix membranes and graphene-based membranes (Shen, et al., 2016)) to avoid these constraints.

Discussion

Performance of Membrane Technologies in Industrial Wastewater Treatment

Microfiltration (MF) is widely used as a pretreatment process in industrial wastewater treatment to solve this problem because of its ability to filter mechanical impurities, suspended solids, bacteria, and large particulate matter. MF has been shown in many studies to be especially effective in sectors like food processing and textiles. Moreover, the application of the MF to food industries' wastewater results in an average TSS removal rate of 90–95%, such as Harif and Adin (2007) decrease in suspended solids and organic matter. This observation agrees with previous studies that have suggested the role of MF in wastewater treatment as a polish or pretreatment, which lessens the load on higher-end membrane processes like UF and NF (Zeman, & Zydney, 1996).

Although there are merits, such as stable permeate quality and low cost of MF alone, its removal of dissolved components like dyes and heavy metals is limited. Zeman and Zydney (1996) have also mentioned the efficiency of MF modules in retaining large-size particles. However, appropriate measures are needed to be taken because it is not effective towards dissolved type organics or salts; otherwise, another membrane process will be circulated for complete treatment. These are appropriate, but in many situations, such as textile effluent, the dyeing and organic dissolved chemicals in effluent mean that 90% of the total useable water is impractical.

Ultrafiltration (UF) has a smaller filtration capability; it can remove macromolecules, colloids, and high molecular weight organic compounds. UF is well known widely in the textiles and pulp and paper industries where effluent frequently contains proteins, dyes or other large organic molecules. A study by Bazán et al. Tang et al. (2018) reported that high COD and color removal efficiencies could be achieved by using UF processes, reaching COD removal rates of 70–85% and color removal rates over 90% in a study treating textile dyes (Bazán, Gutiérrez, & Pérez-Rangel, 2018). These results emphasize that UF is suitable for industries handling high-molecular-weight organics.

Although UF has tremendous removal efficiency benefits, it is susceptible to membrane fouling (albeit less so than MF), particularly from an effluent with a high organic burden—for example, Zsirai et al. Indications are provided from a range of studies (Yuan et al., 2016) that fouling happens because organic molecules settle and adsorb to the surface of the membrane, which in turn causes a declining permeate flux and increases operational costs by having expensive clean-in-place (CIP) cycles (Wang, et al., 2015). UF is, therefore, an effective treatment. Still, fouling can be a significant problem, and it is generally used in combination with pretreatment methods (e.g., MF or coagulation) to reduce fouling and prolong membrane life.

Operated at a molecular level, nanofiltration (NF) has proved to be a promising alternative for treating wastewater with dissolved salts, dyes as well as organic compounds. For instance, in the textile industry, NF stands out for dye removal in natural water; electrodes are then immersed in a solution. Gapswiller et al. (2004) published results of over 95% dye rejection (Wang, et al., 2015). Tang et al. NF membranes remove not only a high dye removal but also small organic molecules and salts, which are dissolved within the production process to facilitate treated water reuse (Bahadur et al. 2009). This underlines that NF could benefit from water purification and resource recovery, which is essential for industries that are promoting sustainable solutions.

Table 1. Comparison of Membrane Technologies for Wastewater Treatment

Membrane Technology	Target Contaminants	Efficiency	Applications	Energy Consumption	Reference
Microfiltration (MF)	Suspended solids, bacteria	90-95%	Food processing, textiles	Low	Abdel-Shafy & Abdel-Shafy, 2017
Ultrafiltration (UF)	Colloids, macromolecules	70-85% COD, 90% Color	Textiles, pulp and paper	Medium	Sadr & Saroj, 2015

Nanofiltration (NF)	Dissolved salts, dyes	> 95% dye removal	Textile effluents, metal plating	Medium-High	Torkashvand et al., 2021
Reverse Osmosis (RO)	Dissolved salts, heavy metals	99% removal of heavy metals	Metal plating, desalination	High	Bera et al., 2022
Ceramic Membranes (CM)	Oil, heavy metals, organic pollutants	High	Petrochemical wastewater	Low-Medium	Asif & Zhang, 2021
Membrane Bioreactor (MBR)	Organic matter, nutrients	High	Municipal wastewater	Medium-High	Neoh et al., 2016
Bioelectrochemical Membranes	Organic matter, ammonia	High	Advanced treatment	Very Low (energy-efficient)	Yuan & He, 2015

However, a fundamental limitation of the NF technology is that it is much more fouling-prone-prone, especially at complex effluents like organics/wax or even oil-in-water emulsions. Fouling decreases membrane effectiveness and increases operational costs. Ahmad et al. In the NF membranes, fouling is mainly related to organic components and biofouling, as reported by (2014) in petrochemical wastewater. Although pretreatment processes can reduce fouling, NF will still need cleaning and replacement from time to time, which in turn increases operational costs.

The most advanced membrane technology, Reverse Osmosis (RO), which effectively removes 99 of the smallest dissolved molecules, has been used in various applications throughout many industries, including metal plating and petrochemicals. RO is the best technology in wastewater with high salinity or dissolved heavy metals because it can partially replace ion exchange technology. For instance, Kosutic et al. Pinteala et al. (2007) reported that RO brought metal concentration with more than 99% reduction possibilities, and ROS is much greater than the legally defined upper permitted dispatch limits. Similarly, Greenlee et al. RO has interestingly received considerable scientific interest as the work of Verliefde et al. (2009) showed high rejection percentages of dissolved salts and was, therefore, ideal for desalination in water-scarce areas.

Yet, reverse osmosis is not perfect. The operation at high pressures results in higher energy consumption; this is primarily seen in applications where the osmotic pressures are high, as is the case of desalination or metal recovery (Elimelech, & Phillip, 2011). In a study on tuning NF membrane performance in treating BNR WW, the researchers presented that although advancement has been made to reduce energy consumption in conventional RO systems — fouling continues to be one of the significant issues with these systems, particularly when treating high levels of organics or emulsified oil present in WW (Choudhury, Wlodarczyk-Makula, & Cichon, 2018). In the petrochemical industry, Elimelech and Phillip (2011) noticed that almost every RO system suffered organic fouling or biofouling while this was quite rarely observed on the side of salt fouling. As a result, although the RO system has the best removal efficiency, it is not economically feasible in specific industrial applications or on a large scale unless energy recovery systems and or renewable energy sources are implemented.

Sustainability Implications of Membrane Technologies

A key advantage of membrane technologies is their role in providing a means for water reuse and resource recovery, which are fundamental components of sustainable industrial practice. Reused water from sewage enters the reuse and return balance in many long-term industrial projects such as textile or petrochemicals due to increasingly limited water resources and strict environmental regulations. Membrane technology, in particular NF and UF, depending on the studies, can recover up to 50-60% of treated water that may be recycled in industrial processes (Wang, et al., 2015). It reduces water consumption and wastewater discharge, helping industries meet effluent disposal limits.

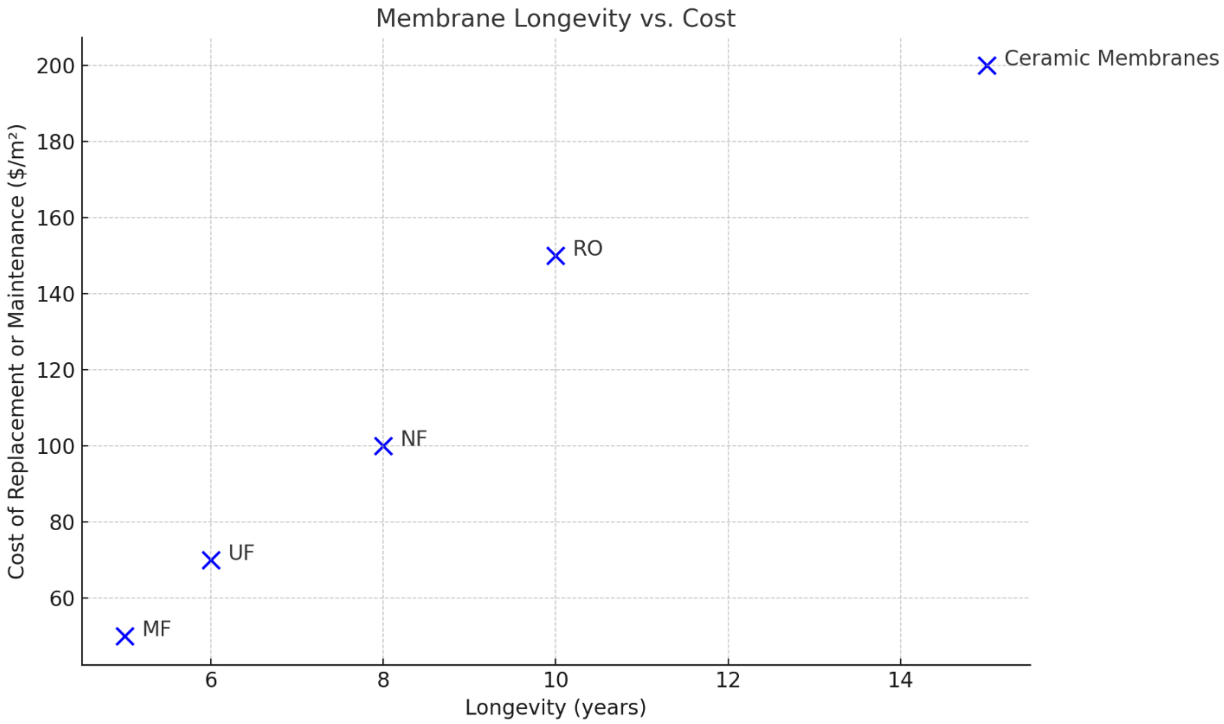

Figure 2. Membrane Longevity vs. Cost graph

A huge part of sustainability is also the reconciliation of valuable substances from wastewater. For example, in industries like metal plating containing heavy metals, copper and zinc in effluent, reverse osmosis and nanofiltration are used for recovery of these metals, reducing environmental impact due to waste disposal or allowing the reuse of these metals into production (Kosutic, Dolar, & Asperger, 2007). This falls in line with the larger ambitions of a circular economy that collectively reduces waste and cycles resources back into production repeatedly.

Though, even with this benefit to sustainability in mind, the significant energy requirements that come with some membrane processes --especially RO --call into question their long-term feasibility. Elimelech and Phillip (2011) emphasize that RO is the most practical treatment system for desalination and metal recovery. However, it consumes more energy than other membrane processes, such as UF or MF. The enormous energy requirement associated with membrane systems has created an intensified demand for renewable energy sources to be integrated into this form of energy-intensive process to lower the cost of operation as well as thus reduce carbon emissions.

Challenges in Industrial Applications

Although the introduction of membrane technologies in industrial wastewater treatment has shown a positive outcome, there are still several challenges that need to be tackled. Even then, membrane fouling is widely accepted as the most significant operational challenge in all membrane technologies. Fouling not only diminishes the efficiency of a membrane but also necessitates more frequent cleaning and replacement, which leads to higher operational costs. (1999), the fouling in R O systems (especially by organics and biofilms) resulted in up to 20–30% decrease in permeate flux, which necessitates frequent chemical cleaning. Likewise, the major problem in the water treatment industry is a substantial reduction in performance due to the fouling of UF and NF membranes, mainly when a high organic load or refined emulsified oil exists.

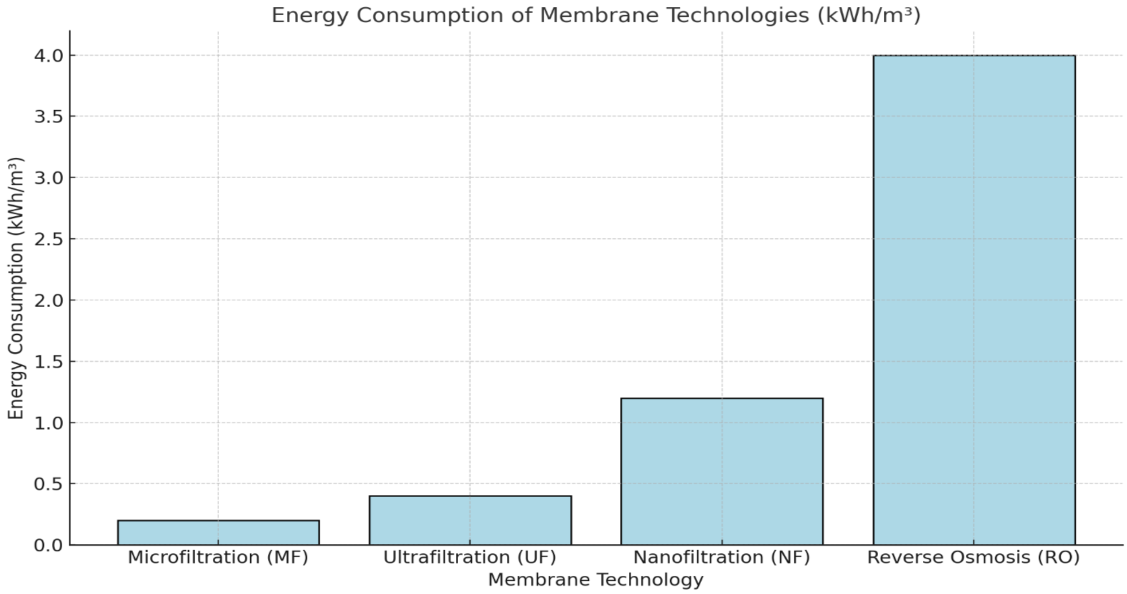

Figure 1 Energy Consumption Bar Chart

The costs of membrane systems are very high, and this is a significant obstacle, especially for advanced systems like reverse osmosis. Although membrane systems have lower operational costs than traditional activated sludge plants in the long run, significant upfront investment is required for membrane modules, pumps, and pretreatment systems, which can be marginal for small industries. This has resulted in limited acceptability of these technologies, especially in resource-poor response countries (Singh, & Hankins, 2012). More affordable membrane materials must be developed and the role of life-cycle analysis in economically rationalizing membranes needs to be recognized if these technologies are to become mainstream.

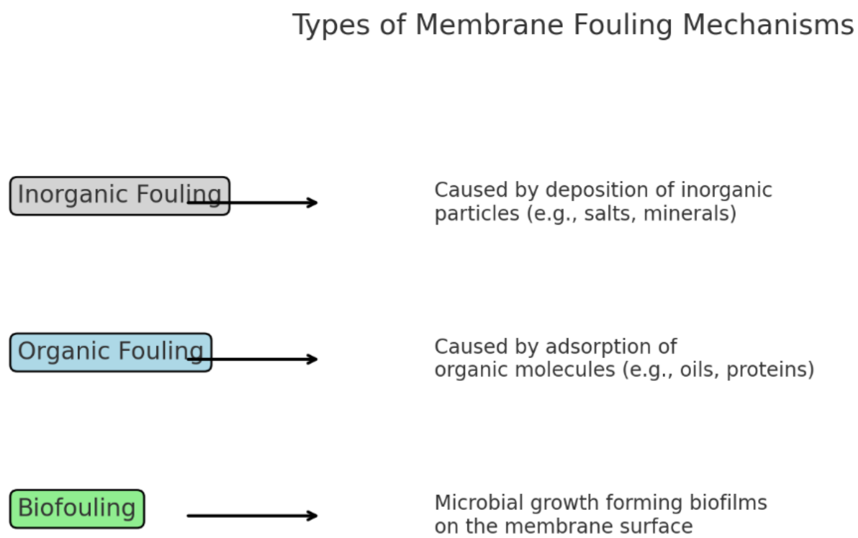

Figure 4. Fouling Mechanism Illustration

Finally, variability in wastewater composition poses a challenge to the effectiveness of membrane technologies. Industries like textiles or petrochemicals often produce effluents with highly variable concentrations of pollutants, making it difficult to maintain consistent membrane performance. While pretreatment methods can alleviate some of these challenges, there is still a need for more robust, versatile membrane materials that can handle fluctuating contaminant loads without compromising performance (Ahmad, Danish, & Hashim, 2014).

Future Directions

While membrane separation technologies have significantly improved industrial wastewater treatment, there are several opportunities for innovation to enhance performance further, reduce costs, and expand their applicability across diverse industries. Below are the key areas that future research and development should focus on to address current limitations and unlock the full potential of these technologies.

Development of Anti-Fouling and Fouling-Resistant Membranes

The most challenging problems occur in membrane technology due to membrane fouling, reducing efficiency and increasing operational cost. Fouling is when organic compounds, microbial growths, or inorganic particles accumulate on the membrane surface, clogging the pores and effectively increasing the rate of resistance. The consequence is more cleaning, higher energy demand, and reduced membrane life span.

This will require the development of anti-fouling membranes to be a priority for future research. The application of surface modification, where membranes are imparted with a hydrophilic coating or manufactured as nano- or micro-structured surfaces, has proven to reduce the extent of foulant adhesion. Furthermore, the development of anti-fouling materials (e.g., hybrid composite membranes) could avoid classical fouling troubles meanwhile ensuring a superior filtration performance. The development pathway offers promise in the creation of self-cleaning membranes, recognizing environmental cues like temperature or pH to trigger an automatic rejection of contaminants. These advances would dramatically increase the service life of membranes and reduce cleaning downtime so that better efficiency could be obtained at the process level.

Integration of Hybrid Membrane Systems

Individually, these membrane technologies (e.g., microfiltration [MF], ultrafiltration [UF], nanofiltration [NF], and reverse osmosis) have proven quite effective, but combining them into hybrid systems can usually provide improved treatment performance. Hybrid membrane systems include the best of multiple technologies, providing solutions for the unique removal of different contaminants in one process. For example, combining ultrafiltration with reverse osmosis can treat both macromolecular impurities and dissolved salts in a single integrated treatment system, eliminating the requirement for separate multi-stage treatment and pretreatment steps.

Furthermore, in addition to using multiple membrane types together, hybrid systems also have the potential for combinations with other treatment methods, such as biological processes, advanced oxidation techniques, and even control tools. While this method does improve pollutant elimination, it also provides a way more comprehensive treatment for compound wastes, most notably in industries that have remaining water that has vastly differing compositions. Future research should mean adapting these systems in a way that cost-effective and energetically viable wastewater treatment would be secured with maintained environmental standards.

Energy Efficiency and Renewable Integration

High-pressure processes, including reverse osmosis, still have a significant energy issue. For the future, it is essential to develop energy-efficient membrane systems. Among the most recent developments is continued improvement in low-pressure membrane processes that offer high levels of contaminant rejection at a potentially reduced energy footprint. New membrane materials allowing faster flow or higher permeability through the membranes will be crucial to reducing energy requirements infiltration.

One other area for serious meltdown is the incorporation of renewable energies (like solar or wind power) into membrane operations. For example, a number of solar-powered desalination plants are already set up within water-scarce locations around the globe, and employing equivalent ideas to industrial wastewater treatment might help lower the energy burden connected with membrane technologies. And they can take advantage of clean energy sources, reducing their carbon footprint in the end making them a more attractive option for industries looking to minimize their environmental impact.

Membrane Durability and Cost Reduction

One of the significant challenges impeding the broad applicability of advanced membrane technologies is capital costs, such as high membrane costs incurred by demand for system replacement and maintenance due to mechanist fouling or wear. Efforts in the future should instead be aimed at developing long-lasting membranes that can work effectively in severe industrial surroundings.

They can strive to bring membrane costs down — thereby making them more affordable for small-to-medium sized enterprises. For these reasons, new fabrication techniques like 3D printing or roll-to-roll manufacturing could help reduce material and production costs. Furthermore, the growth of robust ceramic or composite membranes will also reduce chemical leaching and thermal degradation for long-term use in membrane technologies across many diverse sectors.

Customization for Industry-Specific Applications

Each different industry will produce very different wastewater, from high organic loads in food processing to heavy metals in metal plating. In the future, any membrane technology will need to be further customized for the industry due to industry-specific needs. For example, membranes may be developed to specifically target specific contaminants, i.e., dyes in textile industries or emulsified oils in petrochemical sectors.

Therefore, it will be possible to develop modular membrane systems in this context (& Section 5) with the result that industries can take steps to modify their wastewater treatment processes when faced with different effluent compositions or regulatory requirements (e. g.). That flexibility could be essential for maximizing treatment efficiency and minimizing operating costs in wastewater sectors that have high variability in their wastewater profiles. The flexibility and customization of membrane systems will be necessary in making these technologies relevant and effective across the range of industrial applications.

Circular Economy and Resource Recovery

One of the most significant emerging trends is the circular economy, where waste is minimized and materials are used over and over. This latter aspect of resource recovery proffers a grand opportunity for membrane technologies in the transitional phase. As an example, nanofiltration and reverse osmosis have already shown promise in recouping precious metals, salts, and chemicals from industrial effluents. Future research should investigate the degree to which these processes can be intensified for high recovery and commercial feasibility.

This would also enable the development of next-generation membrane systems that are optimized not only for water purification but also for byproduct recovery on a commercial scale. Such dual functionality would obviously enable the membrane component to play a significant role in industrial resource recovery strategies – thus marrying wastewater treatment with broader sustainability aspirations and reducing the waste footprint of industries as well.

Conclusion

The development of membrane processes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis initiated a revolution in the field of industrial wastewater treatment. You can learn more about these technologies, how they work, and the far-reaching benefits of producing potable water with as little energy input using them, which have emerged by effectively removing a diverse range of contaminants. Nevertheless, certain issues (membrane fouling, high capital costs, and diversity in industrial wastewater uptakes) are barriers to the broader application of these technologies, especially in small- to medium enterprises.

This is a field that requires ongoing research, anti-fouling materials development, and hybrid systems along with energy-efficient solutions. Developments, including self-cleaning membranes and the incorporation of renewable energy sources in membrane operations, offer great potential to improve sustainability with economic viability for these technologies. In addition, as industries adopt more of a circular economy mandate for the way they operate then membrane technologies will become key in changing waste to resource and turning wastewaters into part of industrial value chains while also meeting increasing environmental standards reducing their ecological footprint.

In summary, membrane technologies have some limitations. Still, there is clear room for innovation in their technology, and scaling them up is one of the significant tools to meet the growing global need for sustainable wastewater treatment. Further research and development aimed at enhancing membrane performance, cost reduction, and tailoring of the technologies for sector-specific requirements would complement sustainable industrial wastewater treatment in a more energy-efficient manner.

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