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Comprehensive Review of Membrane Fouling Control Mechanisms

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Abstract

One of the biggest problems with membrane-based separation procedures is membrane fouling. As particles, organic matter, microbes, and other materials build up on the membrane's surface or inside its pores, the effectiveness of membranes – such as those used in reverse osmosis, ultrafiltration, and microfiltration – declines over time. The effectiveness and longevity of the membrane are eventually lowered because of this fouling, which causes a drop in flux and a rise in transmembrane pressure (TMP). Cake formation (concentration polarization), membrane pore blocking, organic fouling, inorganic fouling (scaling), biofouling, colloidal fouling, chemical fouling, fouling, due to an imbalance in hydrophobicity or hydrophilicity, and fouling resulting from an imbalance in hydrophobicity or hydrophilicity are some of the mechanisms of membrane fouling. Numerous techniques have been used to address fouling problems, such as pre-treating the feed water, cleaning the membrane surface chemically and physically, altering the membrane's characteristics, and optimizing operational parameters like temperature, transmembrane pressure, and crossflow velocity. The outcomes of these tactics have been encouraging. Many membrane modules have been developed to solve these issues, but their ability to enhance the membrane surface is severely limited. Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) are the result of these difficulties. DSEMFPs' special shear-controlling capabilities efficiently lessen fouling and contribute to the maintenance of acceptable flux levels. Additionally, they have an edge over other fouling mitigation strategies due to their integrated self-cleaning feature. To improve comprehension and eventually streamline and simplify the use of membrane-based separation processes at bigger scales, a thorough examination of each of these fouling extenuation techniques is necessary. To determine the best strategies for reducing fouling, a thorough analysis of the different fouling control techniques is essential.

Key words: Membrane, fouling, concentration polarization, Pore blocking, biofouling, crossflow module, Dsemfps

INTRODUCTION

Concentration polarization and the ensuing fouling pose serious problems for membrane-based separation technologies [1, 2]. It is crucial to comprehend the nature of fouling before attempting to resolve these problems. Unwanted elements build up and stick to the membrane's surface or inside its pores, a process known as membrane fouling, which reduces the effectiveness and efficacy of filtration. This phenomenon is very prevalent in desalination and water treatment procedures. Fouling increases the need for frequent cleaning and maintenance, lowers membrane permeability, and raises operating expenses.

Physical treatments [3], chemical treatments [4], gas sparging [5], back flushing [6], back washing [3], and many other techniques have been employed

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to lessen fouling. These methods all show varying degrees of efficacy. They do, however, have certain disadvantages. For instance, chemical treatments might take a long time to clean and frequently call for new chemicals. Furthermore, back washing and back flushing may weaken the membrane's structure.

Some sophisticated modules are then created. Standard crossflow modules are the first step in this process, which then moves on to Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs). Shear on the membrane surface is controlled by standard crossflow modules [7], which aid in concentration polarization and fouling management. Nonetheless, the feed flow rate affects the shear rate. While a larger feed flow rate can result in less-than-ideal use of the membrane surface area, which eventually affects permeate throughput, a lower feed flow rate is less efficient at controlling fouling [8].

Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) are an efficient way to overcome the drawbacks of conventional filtration techniques [9]. The Couette flow module, which was created in 1985 to effectively collect plasma from donors, marked the beginning of the development of DSEMFPs [10]. Subsequently, standard crossflow modules were adapted to the Rotating Disk (RD) [11] and Rotating Disk Membrane (RDM) [9] configurations by simply adding one or two rotational components to the existing module designs.

In response to the need for increased membrane surface area and improved in-built cleaning mechanisms, two new membrane modules were developed: the Spinning Basket Membrane (SBM) [12] module and the Intermeshed Spinning Basket Membrane (ISBM) [13] module. Remarkable analyses have been conducted on these DSEMFPs.

To find the best solutions that would enhance membrane performance in separation processes, a thorough examination of the many fouling problems and associated mitigation techniques is necessary.

TYPES OF FOULING

The buildup of undesirable materials on a membrane's surface or inside its pores, such as organic debris, inorganic salts, microbes, or particles, is referred to as membrane fouling. This buildup reduces the effectiveness of filtration or separation processes, leading to decreased performance. It is essential to understand the type of fouling present before implementing any treatment processes.

There are various typical classifications for this fouling. Organic fouling [14–16], inorganic fouling [17–19], biofouling [20, 21], and particle fouling [22] are the first four types of fouling.

- *Organic Fouling*: When organic materials, like proteins, humic substances, or polysaccharides build up on a membrane's surface, it's known as organic fouling. These substances may come from biological development, industrial wastewater, or natural water sources. The development of a gel or cake layer that prevents water from passing through the membrane is a common characteristic of organic fouling. Organic fouling has been the subject of extensive research. Figure 1 shows how organic foulants are affected by temperature.
- *Inorganic Fouling (Scaling)*: Inorganic substances can precipitate and create deposits on the surface of membranes, obstructing their pores. This is especially true with salts like silica, calcium carbonate, and calcium sulfate. This problem is particularly common in desalination procedures since the feedwater frequently has significant salt concentrations. The performance of membranes can be severely hampered by scaling, which also makes chemical cleaning more important. The inorganic fouling on the membrane surface is clearly visible in Figure 2.
- *Biofouling:* When bacteria, algae, or fungi proliferate on a membrane's surface, it's known as biofouling. Biofilms may form because of this process, which can obstruct the membrane's pores and result in other chemical alterations that increase the membrane's vulnerability to deterioration and corrosion. Figure 3 shows a simplified representation of biofouling.

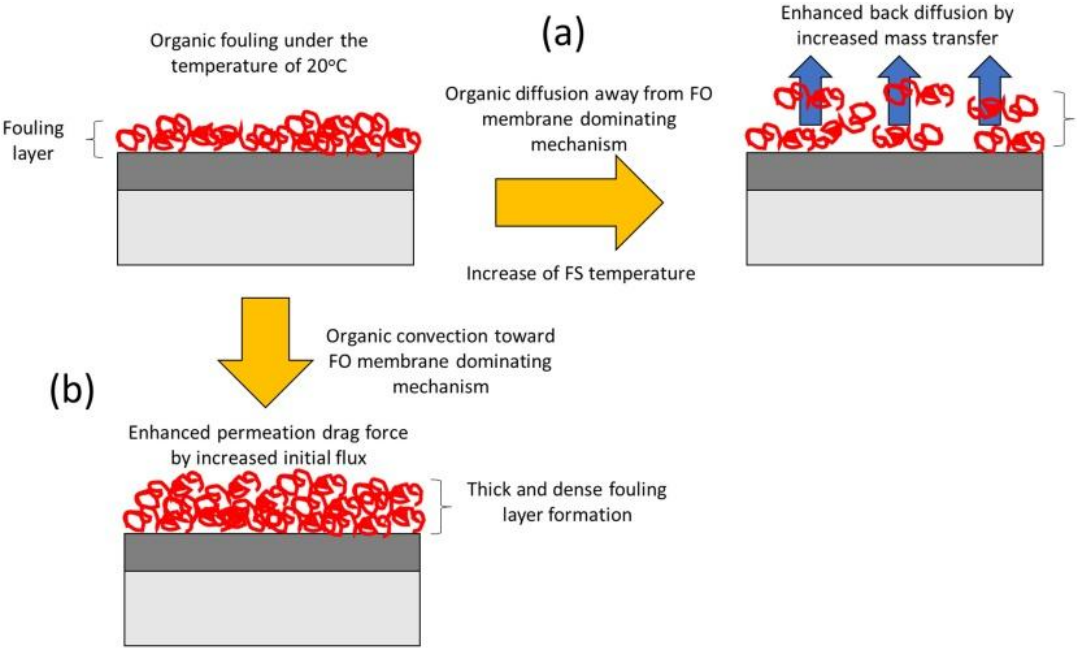

Figure 1. An illustration of how temperature affects sodium alginate, an organic foulant: Temperature increases from 20 to 35 °C (loose and thin fouling layer) and 20 to 50 °C (thick and dense fouling layer) are shown in (a) and (b) respectively [23].

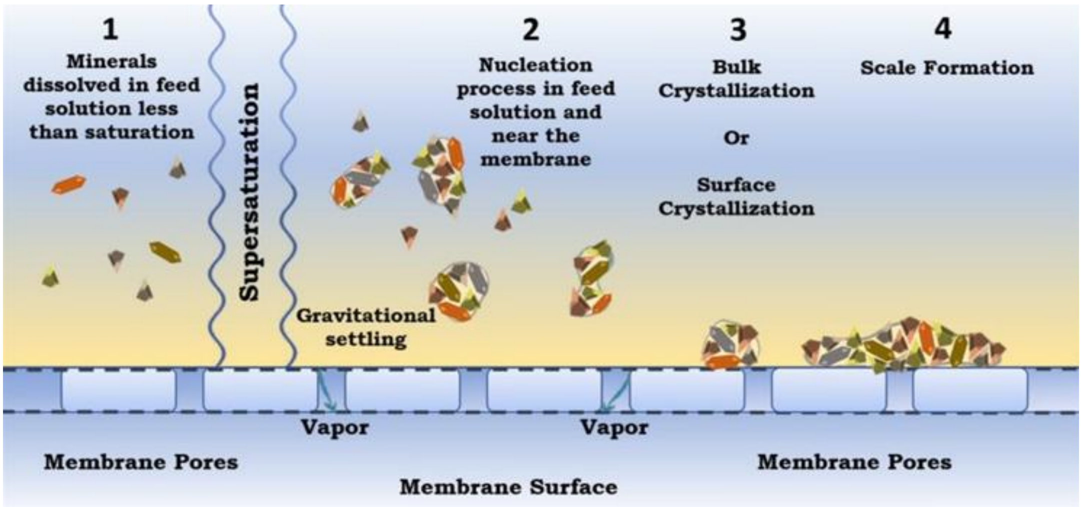

Figure 2. Steps for Inorganic fouling in a membrane system [24].

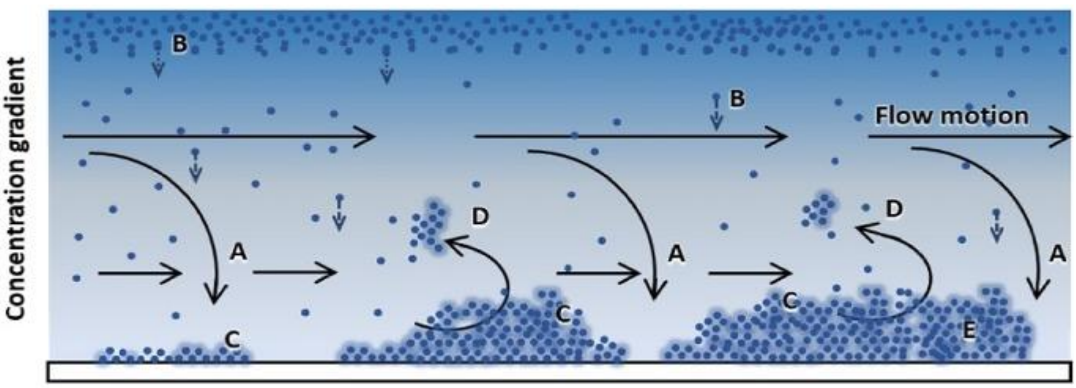

Figure 3. Process of Bio-fouling development [25].

- *Particulate Fouling:* The holes of membranes can get clogged by solid particles like dirt, clay, or other suspended materials. This kind of fouling can be especially troublesome in procedures, like microfiltration and ultrafiltration, and is frequently associated with suspended solids in feedwater. A SEM image of silica dioxide particle fouling is presented in Figure 4.

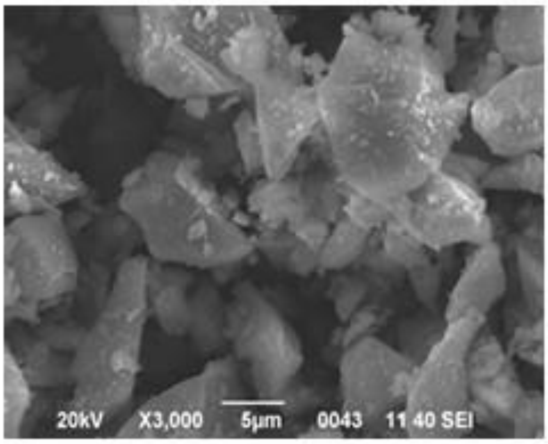

Figure 4. Sem photograph of silica dioxide particulate fouling [26].

FOULING MITIGATION TECHNIQUES

Reduced filtration effectiveness, higher energy consumption, higher operating expenses, and a shorter membrane lifespan are just a few of the detrimental effects that membrane fouling can cause. Several strategies are used to overcome this problem. These include creating fouling-resistant membrane materials or coatings, cleaning the membranes chemically or physically, and pretreating the feedwater by filtering or chemical dosing. Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) significantly contribute to the fouling control process due to their feed flow rate-independent mechanism for controlling shear. Figure 5 illustrates different types of DSEMFPs. Figure 5(a) shows a Rotating Disk (RD) module, where the disk rotates above the membrane surface, facilitating the removal of solutes from the surface. Following that, Figure 5(b) depicts a Rotating Disk Membrane (RDM) module, in which both the disk and the membrane are capable of rotation. This design effectively helps in alleviating solutes from the membrane surface. To increase the surface area of the DSEMFPs, various other modules have been designed, among which the Multiple Shaft Disk (MSD) module stands out, as shown in Figure 5(c). Despite these advantages, cleaning the membranes remains a significant challenge for users. To address this, self-cleaning DSEMFPs have been developed, such as the Spinning Basket Membrane Module (SBM) and the Intermeshed Spinning Basket Membrane Module (ISBM). In both cases, there is one shaft (for SBM) and two shafts (for ISBM) attached to baskets. These baskets feature four arms, with membranes located on the surface of alternating arms. When the basket rotates in a clockwise direction, the fluid easily passes through the membrane at the arm of the basket due to the position of the feed inlet. Conversely, the reverse rotation of the basket creates a vacuum in front of the membrane side, allowing accumulated solutes to be easily dislodged from the membrane surface. This self-cleaning mechanism makes these two modules particularly valuable in the separation industry Figure 5(a–e).

Moreover, the fouling mitigation techniques are classified in the following ways.

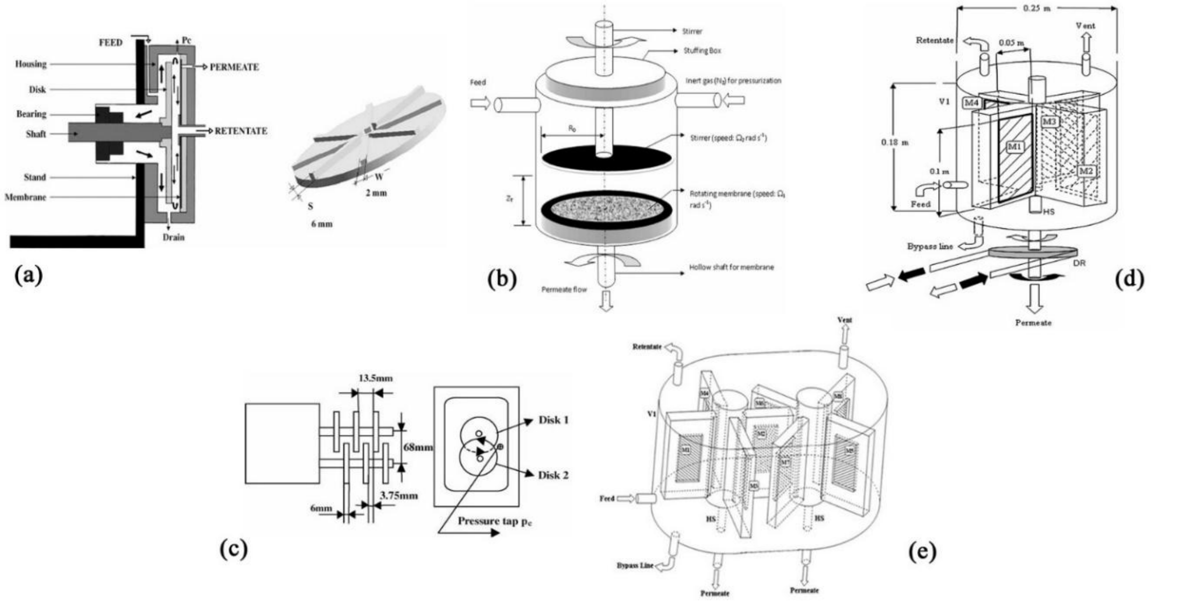

Figure 5. Schematic of (a)RD [27], (b) RDM [9], (c) MSD [28], (d) SBM [29], (e) ISBM [13].

Pre-Treatment of Feedwater

a. *Coagulation/Flocculation:* applying coagulants, such as ferric chloride or alum, to the particles to cause them to aggregate into bigger flocs that are simpler to filter out before they reach the membrane [30].
b. *Filtration:* removing bigger particles from the feedwater before it reaches the membrane by using a secondary filtration step (such as multimedia filters or sand).
c. *Activated Carbon:* Fouling can be decreased by adsorbing organic chemicals and chlorine before to the membrane system [31].
d. *Softening:* Scaling on membranes can be avoided by utilizing chemical softening techniques to remove ions that cause hardness, such as calcium and magnesium.

Membrane Surface Modification

a. *Hydrophilic Coatings:* By decreasing membrane adsorption, increasing the hydrophilicity of the membrane surface can lessen organic and protein fouling [32].
b. *Surface Charge Modification:* By inhibiting the adherence of particles with identical charges, altering the membrane's surface charge can aid in fouling reduction [33].
c. *Anti-fouling Polymers:* applying polymers that can repel impurities or withstand fouling to the membrane surface [34].

Periodic Cleaning

a. *Chemical Cleaning:* removing fouling materials (such as scaling and biofilm) from the membrane surface using acids, alkalis, or detergents. Citric acid (for scale), sodium hydroxide (for organic fouling), and surfactants are examples of common cleaning agents [4].
b. *Enzyme Cleaning:* Enzymatic cleaning can aid in the breakdown of organic fouling substances, especially when it comes to biofouling (such as proteins and polysaccharides) [35].
c. *Reverse Flow or Backwashing:* Particles and biofilms can be removed from the membrane surface by regularly reversing the feedwater's flow direction [3].
d. *Pulsed or Continuous Backflushing:* involves flushing the membrane with high-pressure water on a regular basis to get rid of accumulated foulants [6].

Operational Adjustments

a. *Flux Control:* By slowing the accumulation of particles or organic compounds, fouling can be decreased by lowering the permeate flux, or the amount of water that passes through the membrane [36].
b. *Crossflow Velocity Optimization:* By strengthening the shear forces that keep the particles suspended, increasing the crossflow velocity helps lessen the buildup of foulants on the membrane surface.
c. *Operating Pressure:* By lessening the pressures forcing impurities into the membrane, lowering the operating pressure can assist reduce fouling.

Antimicrobial Agents

a. *Biocides:* Incorporating biocides, like hydrogen peroxide, ozone, or chlorine, can help stop or manage biofouling by eliminating bacteria before they develop biofilms on the membrane.
b. *UV Radiation:* Without the use of chemicals, microbial fouling can be decreased by disinfecting water with UV light before filtering [37].

Membrane Modifications and Innovations

a. *Nanocoatings:* By producing smoother surfaces that stop foulants from building up, coatings made of nanomaterials (such as graphene oxide and carbon nanotubes) can greatly increase fouling resistance [38].
b. *Electrokinetic and Electrochemical Methods:* enhancing the removal of particles or microbes from the membrane surface by applying electric fields [39].
c. *Membrane with Dual Layer Design:* By maximizing flux distribution throughout the membrane, membranes having an outer active layer and an inner support layer can aid in fouling reduction.

Advanced Oxidation Processes (AOPs)

a. *Ozone or UV-Hydrogen Peroxide:* Before organic foulants reach the membrane surface, they can be broken down into smaller, easier-to-manage components by combining hydrogen peroxide with ozone or UV [40].

Use of Additives

a. *Anti-Scaling Agents:* To stop mineral scaling on the membrane, chemicals, like polyphosphates or phosphonates, can be added to the feedwater [41].
b. *Dispersants:* By preventing particle matter from clumping together, dispersants can lessen fouling brought on by suspended solids.

Membrane filtering systems can preserve peak performance, save maintenance costs, and increase membrane life by combining various methods according to the kind of fouling (e.g., scaling, organic, biological, or particle).

CONCLUSIONS

Membrane fouling is a major problem for sectors, like wastewater treatment, food processing, and water desalination, that depend on membrane-based separation techniques. It happens when undesirable substances, such as suspended particles, inorganic salts, organic compounds, or microbes, build up on a membrane's surface or inside its pores and impair its functionality. The process becomes less efficient due to this fouling, which raises energy consumption, operating expenses, and the need for more regular membrane repair or replacement. In the context of water desalination, for example, membranes are used to separate salt from seawater to produce fresh water. Fouling can severely obstruct this process by blocking water flow through the membrane, which in turn raises the pressure required to maintain the desired water production rate. Similarly, in wastewater treatment, membranes help to separate contaminants from treated water. When fouling occurs, the system's ability to effectively clean the water is compromised, increasing the risk of pollutants entering the environment.

Researchers are actively investigating the mechanisms behind membrane fouling to understand how and why it happens. This research includes examining the types of materials that contribute to fouling, the conditions that exacerbate it (such as temperature, pressure, and pH), and how fouling interacts with the membranes' physical and chemical properties.

The goal of ongoing research is to create better methods for managing and preventing fouling. This includes optimizing membrane materials and surface treatments to enhance their resistance to fouling, creating cleaning methods to effectively restore membrane performance, and exploring alternative filtration technologies. For instance, advanced coatings and surface modifications can help reduce the adhesion of foulants to the membrane surface, while innovative cleaning techniques – such as chemical cleaning, physical cleaning (like backflushing), or electrochemical methods – can assist in removing fouling and extending the lifespan of membranes.

Ultimately, improving resistance to and management of fouling is essential for enhancing the efficiency and sustainability of membrane-based processes. This can help mitigate operational costs and ensure these technologies can meet the increasing demands of industries like water desalination, food processing, and wastewater treatment.

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