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Advancements and Challenges in Membrane Bioreactor Technology for Industrial Wastewater Treatment

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Abstract

Due to its success in achieving the majority of wastewater treatment objectives, Membrane Bioreactor Technology (MBR) has replaced the Conventional Activated Sludge Process (CAS) as the leading method for treating wastewater. Nowadays, the treatment of industrial wastewater become one of the world's major concerns, MBR technologies are used more frequently. This technology has a bright future in wastewater treatment (especially industrial wastewater). In general, this article is designed to give a general view of various aspects of an MBR, with the aim of addressing and overcoming any potential drawbacks or limitations. In this work, the fouling in MBR technology its variations and mechanisms, influencing factors are also discussed in detail. However, membrane fouling is thought to be the biggest challenge this technology faces. One of the main agents that causes the fouling of the membrane is Extracellular Polymeric Substances (EPS), which results in a decrease in filterability and a decline in membrane flux, which affects the membrane lifespan. Furthermore, it looks into how to minimize membrane fouling in MBR systems and offers biological tactics to lessen the likelihood of membrane fouling in MBR technology. Finally, this work quoted also how artificial technology might help to increase removal effectiveness and prevent filtering membrane obstruction.

Keywords: MBR technology; Membrane fouling; Control; Mechanisms; Operating parameters

Abbreviations: MLSS: Mixed Liquor Suspended Solids; EPS: Extracellular Polymeric Substances; SMP: Soluble Microbial Products; HRT: Hydraulic Retention Time; TMP: Transmembrane Pressure; SRT: Sludge Retention Time; Mbrs: Membrane Bioreactor System; MIEX: Magnetic Ion Exchange Resin; BAC: Biological Activated Carbon; EO: Electroxidation

Introduction

In recent decades, several factors like population growth, urbanization, industrialization, climate change, and the expansion of irrigated agriculture have contributed to a change in the global demand for freshwater. This has resulted in water scarcity becoming a significant challenge for almost all countries worldwide [1]. To address this issue, there is currently a high demand for recycling water through the use of advanced treatment technologies, such as industrial and municipal wastewater treatment, in order to alleviate water shortages. The World Economic Forum's 2019 report recognized freshwater scarcity as one of the biggest global risks with potential large-scale impacts in the next decade. In light of this, industries worldwide need to place a greater emphasis on adopting sustainable water treatment practices, wastewater recycling, and wastewater reuse for various purposes. These efforts can help reduce the strain on freshwater supplies and promote a more sustainable approach to water management.

The process of biological wastewater treatment utilizes microorganisms such as bacteria to eliminate pollutants from water. This type of treatment employs a variety of techniques, ranging from conventional activated sludge methods to cutting-edge technologies like membrane bioreactor systems (MBRs). Biological wastewater treatment technologies have gained popularity worldwide because they are both effective and cost-efficient compared to many chemical and physical treatment processes.

Membrane bioreactor systems (MBRs) are a compact technology that combines the activated sludge process with membrane filtration in order to treat and recycle wastewater. The membrane bioreactor has been widely utilized for different wastewater treatment (municipal and industrial) and reclamation [2]. This technology integrates a suspended growth bioreactor with a permeable membrane mechanism, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), or reverse osmosis (RO). MBRs are recognized as a well-established and mature technology for wastewater treatment globally, demonstrating significant pollutant removal efficiency. The MBR market reached a value of US$3.3 billion in 2021, and it is projected to reach US$5.8 billion by 2027 according to IMARC Group projections. MBRs are considered a groundbreaking innovation in wastewater treatment, addressing the limitations of conventional activated sludge processes, such as the need for large secondary clarifiers, challenges with liquid-solid separation, excess sludge production, and difficulties in removing recalcitrant compounds [3].

In an MBR, membrane filtration is combined with a traditional biological treatment system to effectively separate liquids from solids [4]. MBRs can handle higher organic loads compared to conventional treatment methods (ASP), making them suitable for treating wastewater with specific components that may be hazardous to microbial activity [5]. The long-lasting microbial populations in MBRs contribute to their resilience against environmental changes post-treatment. In addition, MBRs result in improved quality of the treated effluent. The biological component of MBRs, especially in the context of industrial wastewater, plays a crucial role in their effectiveness and efficiency [6]. The microorganisms in MBRs biodegrade organic components in the raw water prior to membrane filtration. Ghimire N, et al., Razavi SMR, et al., Le-Clech P, et al. [7-9] reported that temperature, pH, wastewater composition, F/M ratio (food to microorganisms), airflow rate, MLSS concentration (mixed liquor suspended solids), SRT (sludge retention time) and HRT (hydraulic retention time) are all parameters that influence microbial activity and the treatment of wastewater in the bioreactor. MBRs are resilient systems that can process wastewater from a variety of industrial sources. Studies by Liu J, et al. [10] and Mubbshir S, et al. [11] demonstrated that a two-stage Anoxic/Oxic-MBR system was effective in removing pollutants from landfill leachate, achieving average removal efficiencies of 85.6% for COD and 80.7% for TN [10,11]. Furthermore, Ariaga S, et al.[12], the MBR polishing step primarily removes particulate matter, it reduces the cost of pathogenic bacteria removal and inactivation [12]. Sun J, al. [13] conducted research on the effectiveness of designed anoxic/aerobic MBR system for hypersaline municipal sewage treatment, in a processing zone (China). The sewage comprised roughly of 80% industrial wastewater and 20% sewage, containing approximately, 1000mg/l [13]. In a separate study, Roy D, et al. [14] proposed the use of a lab-scale submerged membrane bioreactor for treating synthetic leachate for 205 days with four ammoniacal nitrogen concentrations (220, 340, 665, and 1040 mg/L). Their findings concluded that the model was effective in treating high-strength ammoniacal nitrogen [14].

The MBR process has a number of benefits when compared to the ASP, the MBR treatment can achieve high removal efficiencies in domestic wastewater treatment and that MBR permeate is suitable for urban, agricultural, and recreational reuse based on the quality criteria for water reuse [15].

In MBR systems, the membranes replace the need for secondary clarifiers. This leads to a significant reduction in required plant area, as MBRs operate at shorter HRTs and eliminate the need for secondary clarifiers. However, it is worth noting that the MBR method has a few drawbacks, such as the challenge of controlling membrane fouling and increased energy costs [15].

MBR technology has become increasingly popular due to its ability to produce high-quality water, cost-effectiveness, widespread acceptance, and the potential to upgrade existing wastewater treatment plants [16-18].

It is worth noting that academic studies have been conducted to address the two main drawbacks of MBR technology mentioned earlier: membrane fouling and energy consumption. Membrane fouling remains a significant issue in MBR technology [19,20]. It leads to a decline in membrane performance and lifespan, resulting in increased maintenance and operating costs [21].

The accumulation of suspended particulates such as microorganisms, cell debris, colloids, solutes, and sludge flocks are responsible for membrane fouling. These substances are deposited on the surface and within the pores of the membrane, leading to pore clogging and decreased membrane permeability [22].

Membrane fouling in wastewater treatment systems occurs when solid particles are deposited on the surface of the membrane and colloidal particles build up within its pores [23]. This buildup impairs the hydraulic performance of the membrane, causing a decline in permeability and an abrupt increase in transmembrane pressure, which leads to higher maintenance and operating costs due to increased energy consumption and frequent membrane cleaning operations [24,25]. Recent studies have shown that the specific amount of EPS directly correlates with the specific cake resistance, which further exacerbates membrane fouling [26]. To combat this issue, new approaches are needed to reduce membrane fouling, and further research is required to gain a better understanding of the composition and behavior of fouling biopolymers in MBR fouling.

Membrane fouling is a critical issue that limits its application in wastewater engineering. The composition of suspended solids in the mixed liquor suspended solids (MLSS) is the leading cause of membrane fouling [27]. This has prompted recent research into membrane fouling mitigation and expanding the use of MBR technology. This review aims to investigate the reactions and kinetics of biological treatment, assess recent progress in understanding the mechanisms and roles involved in fouling, and propose potential solutions for controlling fouling in MBR systems. The review extensively cites the work of many researchers to gain a comprehensive understanding of the major problem in MBR technologies, which is membrane fouling.

Drawing upon recent and relevant literature on membrane fouling, this article provides an overview of the fundamental principles of membrane fouling and the advancements in approaches to reduce fouling in MBRs. It covers essential information on membrane fouling, including classifications specific to MBRs, and explores the various variables that influence membrane fouling in these systems. Furthermore, the review offers an in-depth analysis of the current research trends in managing membrane fouling in MBRs, shedding light on the latest developments in this field.

Biological Treatment

Type of microorganisms

The majority of microorganisms found in a biological reactor are bacteria, making up more than 90% of the total population. Other organisms present include protozoa, metazoa, filamentous bacteria, algae, and fungi [28]. These bacteria can form pairs, chains, or clusters, while some may exist as single cells. They have diverse metabolic capabilities, utilizing various energy sources such as electron donors, electron acceptors, and carbon sources. These organisms are capable of breaking down various organic and inorganic contaminants, as well as creating the ideal environment for treating specific components present in wastewater. A research project by Shchegolkova NM, et al. [29] used 16S rRNA gene sequencing to analyze the composition of bacteria present in activated sludge and wastewater from three different treatment plants. The research also included a heat map highlighting the top 40 families of bacteria in activated sludge, which accounted for 94.2-97.5% of all bacteria [29].

Bacteria and other microorganisms gather on the membrane's surface, leading to the development of biofilms. As opposed to solitary, free-floating cells, biofilm cells are embedded in a self-made extracellular polymeric substance (EPS) matrix. The EPS contains proteins and carbohydrates, which contribute to the adhesive properties of the biofilm. However, this adhesive nature of biofilms poses a significant challenge in Membrane Bioreactor (MBR) plants [30].

Microbial stoichiometry and kinetics in a bioreactor

In the evaluation of biological treatment performance, balanced microbial stoichiometric equations play a vital role. These equations bear a resemblance to chemical stoichiometric equations but hold immense importance in the biological treatment process. It is important to note that the substrate in the microbial kinetics equation serves a dual purpose, providing energy and aiding the synthesis of biomass. Microorganisms not only act as catalysts for biological reactions but also undergo reproduction, leading to their growth and proliferation throughout the treatment process.

The amount of biomass produced compared to the amount of substrate (such as glucose) consumed can be expressed as biomass yield or growth and is determined by various factors such as microbial composition and growth conditions [30,31].

To understand and analyze the reaction in biological processes, it can be difficult to accurately estimate the speed of the reaction, due to the need to include a wide range of elements in the equation (Table 1). It is important to consider the source and destination of electrons, the necessary nutrients, the amount of biomass present, and the oxidized products when constructing a balanced microbial stoichiometric equation.

Determining the microbial reaction rate is of great importance for various purposes, such as estimating the required volume of the bioreactor and the concentration of biomass needed to achieve a specific outcome. Additionally, the reaction rate can be used to estimate the performance of the bioreactor under specific operating conditions and assist in the design process. To facilitate this, specific software tools like BioWin, STOAT, GPS-X, and WEST have been developed [35].

These software tools use microbial kinetics and establish mass balance equations to reveal important bioreactor performance indicators, such as biomass production rate and substrate concentration in the effluent. Microbial kinetics primarily focuses on optimizing microbial growth rate and substrate utilization [34]. The breakdown of biodegradable substrates through metabolism leads to microbial growth. However, it is essential to note that not all materials in the incoming wastewater are biodegradable. Therefore, determining the amount of biodegradable material in the incoming wastewater is essential for accurately calculating the microbial growth rate.

Furthermore, as microorganisms grow, they also undergo decomposition. The difference between the growth rate and the decomposition rate is referred to as the net growth rate. This net growth rate can be defined as follows:

$$r_{g.net} = r_{growth} + r_{decay}$$

$$r_{g.net} = \frac{dx}{dt} = \frac{\mu_m S\, X}{Ks + S} - k_d X$$

Where:

$r_{g.net}$ is the net growth rate ($g_{VSS} m^3$/day);

X is the biomass concentration (g_{VSS}/m^3);

VSS is the Volatile suspended solids;

S is the biodegradable substrate concentration (g_{COD}/ m^3);

μ_m shows the maximum specific growth rate (day^{-1});

K_S and k_d represent half saturation constant for biodegradable substrate (g_{COD}/m^3)$r_{(g.net)}$ is the net growth rate ($\frac{m^3}{day}$) [32].

This coefficient is critical for understanding how microorganisms utilize their food source, also known as substrate. The rate of substrate uptake is strongly related to the rate of microorganism growth and the biomass yield coefficient.

Although the growth rate of microorganisms is important, engineers are primarily concerned with the substrate removal rate because it indicates the progress of the treatment [35].

In addition, the rate of volatile Suspended solids (VSS) production in the bioreactor is a critical parameter for designing and operating bioreactor facilities. The mixed liquor VSS in the bioreactor are produced from three main sources:

Microorganisms' growth

Non-biodegradable VSSs resulting from biomass decomposition cannot be utilized by microorganisms as substrates.

Non-biodegradable VSSs are generated by the influent, which depends on the characteristics of the wastewater.

The total VSS production rate ($R_{VSS,t}$) can be expressed using the following formula:

$$R_{vss,t} = \frac{\mu_m SX}{Ks + S} - K_d X + f_d k_d X + \frac{X_o Q}{V}$$

Where:

f_d is the fraction of the product of biomass decay that accumulates in a bioreactor;

X_0 is concentration of non-biodegradable;

VSS in waste water influent ($\frac{g_{vss}}{m^3}$);

Q and V represent the influent flow rate ($\frac{m^3}{day}$) and bioreactor volume m^3 separately

MBR Application in Industrial Wastewater

This wastewater can originate from a range of industries including agriculture, food processing, pharmaceuticals, dye manufacturing, metalworking, tanneries, petrochemicals, and textile production, as mentioned in references [36,37]. Despite the varying sources, high-strength industrial wastewater generally contain similar substances such as organic matter, nutrients, viruses, bacteria, microalgae, and toxic compounds [36] (Table 2).

Phuong NTT, et al. [41], reported that the most effective Organic Loading Rate (OLR) for treating oily wastewater in a Membrane Bioreactor (MBR) was 11 kg COD/m^3/day. This resulted in 97.93% removal efficiency for Chemical Oxygen Demand (COD), 71.04% for Total Nitrogen (TN), and 79.04% for Total Phosphorus (TP).

Additionally, Ahmadi M, et al. [42] assessed the effectiveness of a lab-scale MBR in treating oily wastewater from an oil refinery, with different mixed liquor-suspended (MLSS) solids (6.5 and 8.5 g/L) and

Table 1: Different kinetic coefficients of many bacteria existing in MBRs.

MBR characteristics	Biomass type	Yield coefficient	Maximum specific growth rate	Half–saturation coefficient	Decay coefficient	References
SHF-MBR HRT=9.5h, T=14.7°C, MLSS = 6.6g/l.	Heterotrophic bacteria	0.4887 $(\frac{mgvss}{mgcod})$	0.0141(h^{-1})	7.467$(\frac{mgo2}{L})$	0.0521(day^{-1})	[32]
	Ammonium-oxidizing bacteria	1.191 $(\frac{mgvss}{mgcod})$	0.1612(h^{-1})	0.2204 $(\frac{mgN}{L})$	NM	
	Nitrite oxidizing bacteria	0.6473 $(\frac{mgvss}{mgcod})$	0.0786(h^{-1})	0.324$(\frac{mgN}{L})$	NM	
SHF-MBR HRT=9.5h; MLSS=3.3g/l	Heterotrophic bacteria	0.4609 $(\frac{mgvss}{mgcod})$	0.0192(h^{-1})	16.47$(\frac{mgo2}{L})$	Total bacteria decay=0.03034 (day^{-1})	[32]
	Nitifing bacteria	1.0389 $(\frac{mgvss}{mgcod})$	0.272(h^{-1})	0.9329$(\frac{mgN}{L})$		
	Nitrite-oxidizing bacteria	0.7791 $(\frac{mgvss}{mgcod})$	0.1124(h^{-1})	0.4364$(\frac{mgN}{L})$		
IMBR HRT=13h, MLSS=5g/l	*Serratia liquefaciens* and *aeromonas hydrophila* (predominant bacteria)	0.567 $(\frac{mgvss}{mgcod})$	0.0233(h^{-1})	326.14 $(\frac{mgCOD}{L})$	0.062 (day^{-1})	[33]
HRT=33h 25°C	Heterotrophic biomass	0.756 $(\frac{mgvss}{mgcod})$	3.687 $(\frac{mg}{g.h})$	NM	0.353 (day^{-1})	[34]
HF-MBR HRT=8h, T=27°C, and MLSS concentration =1.3g/L.	Heterotrophic biomass	0.703 $(\frac{mgvss}{mgcod})$	NM	NM	0.02(day^{-1})	[35]

MBR-M: membrane bioreactor with microfiltration / IMBR: Immersed MBR/ SHR-MBR: Submerged hollow fiber membrane bioreactor.

hydraulic retention times (12-24 hours). Their findings indicate that the optimal operating conditions to achieve maximum COD removal of 97% were a HRT of 21 hours and MLSS content of 8.2 g/L.

Operating parameters such as Hydraulic Retention Time (HRT), Solid Retention Time (SRT), Mixed Liquor Suspended Solids (MLSS), and Chemical Oxygen Demand to Nitrogen ratio (COD:N) play a crucial role in the treatment process. Optimal operating parameters are necessary to achieve both stable MBR performance and efficient pollutant removal, and numerous studies have investigated their impact on the treatment process.

For example, Melin T, et al. [50] found that a high concentration of MLSS could enhance treatment performance in handling high-strength wastewater. However, this could also lead to membrane fouling. Jiang T, et al. [51] also reported that prolonging the SRT could accelerate membrane fouling, as accumulated matter and high sludge viscosity reduce treatment efficacy. On the other hand, a relatively short HRT could result in a higher organic loading rate (OLR) and reactor volume reduction. Conversely, a longer HRT could improve treatment performance [44,51,52]. Furthermore, the COD:N ratio has been investigated to assess its effects on sludge properties and its role in membrane fouling. A laboratory-scale MBR trial revealed that the membrane performance was significantly improved by raising the COD:N ratio from 100:5 to 100:1.8 [53]. Thus, it is important to note that membrane fouling increases linearly with an increase in MLSS concentration.

Fouling in MBR Technology

The International Union of Pure and Applied Chemistry (IUPAC) Membrane Nomenclature Working Group defines membrane

Table 2: Summary of MBR treatment performances for industrial wastewater.

Type of industrial wastewater	Results	References
Paper-recycling wastewater (real)	HRT: 36 h; SRT: 48; COD: 92-99%	[38]
Pharmaceutical and chemical wastewater (real and synthetic)	HRT: 14 days; SRT: 31-51; COD: 80%	[39]
Molasses wastewater (synthetic)	HRT: 18-20 h; COD: 80%	[40]
Cake shop wastewater (synthetic)	SRT: 50; COD: 97-98%	[41]
Oil refinery wastewater (real)	HRT: 12-24; COD: 74-97%	[42]
Hydrolyzed polyacrylamide containing	SRT: 10; COD: 98%	[43]
Petrochemical industrial wastewater (synthetic)	HRT: 18-24; SRT 25; COD: 99%	[44]
High technology industrial wastewater (synthetic)	HRT: 3.2; COD: 80%	[45]
Dumpsite leachate	COD: 95%	[46]
Poultry slaughterhouse wastewater	COD>94%; fats 99%; SS98%; BOD 97%	[47]
Textile	COD57%; color100%; salinity 30%	[48]
Oily wastewater	Oil and grease 100%; TOC 98%; COD 98% turbidity 100%	[49]

HRT: hydraulic retention time; SRT: sludge retention time; COD: chemical oxygen demand; TOC: Total organic carbon.

Table 3: Factors affecting membrane fouling [58].

Factor	Influence	Type of wastewater
Membrane structure properties	The cake layer in the organic fouling was clearly visible, whereas inorganic fouling did not lead to membrane fouling.	-
	The protein content of the extracellular polymeric substances (EPS) was higher than the polysaccharide content, causing the liquid to become more viscous	Hot white pulp wastewater
Biomass characteristics	A rise in SMP, greater difficulty in filtration, and a decrease in the membrane's performance due to fouling.	Domestic wastewater
	The supernatant SMP had higher protein content than polysaccharides, leading to a thicker texture and making the cake layer easier to form.	Industrial waste
	As the SRT was raised, the SMP and viscosity of the sludge both increased.	Low concentration wastewater
Operating condition	After 30 and 50 days, the sludge flocks had grown larger, the SRT was too low and thus the SMP had risen, resulting in an increased rate of fouling.	Municipal wastewater
	If it was too large, MLSS, SMP, and other microbial products increased-	
	HRT declined, protein substances in SMP increased, and EPS concentration increased	Low concentration wastewater
	HRT decreased, filtration resistance increased, and granular sludge particle size decreased	Artificial wastewater
	Small flocks increased under high-temperature conditions, SMP, and EPS increased, filter cake layer was easy to form	Evaporator condensate
	When the temperature went up, the membrane fouling resistance increased, and the protein content in EPS increased	Hot pulping press

fouling as a decrease in the effectiveness of the membrane due to the accumulation of particulates, microorganisms, cellular debris, colloids, and solutes on the membrane surface, at the pore openings, or within the membrane's pores [54]. This buildup of Total Suspended Solids (TSS) results in a reduction in the membrane's performance [55-57].

Membrane fouling occurs as a result of physicochemical interactions between the pollutants and the membrane material. This can lead to reduced membrane efficiency and, in some cases, the inability of the membrane to effectively treat the required design flows [58] (Figure 1).

Membrane bioreactors (MBRs) have shown to be an effective solution for treating industrial wastewater. However, their widespread commercial application and effectiveness are hindered by membrane fouling and its consequential impacts on operational costs. Membrane fouling is a complex process that is influenced by numerous factors, outlined in figure 2 and table 3. Broadly speaking, these factors can be categorized into four main groups:

1. Membrane properties
2. Biomass characteristics

3. Operating parameters
4. Wastewater characteristics

Determining membrane fouling in MBR technology requires considering the interaction among several parameters. In the context of industrial wastewater, the fouling behavior's complexity and criticality are further exacerbated by the extreme and complicated nature of the wastewater conditions.

Numerous researchers have examined the relationship between various parameters related to wastewater, biomass characteristics, membrane properties, and operating conditions. Table 3 provides an overview of some of the studies that have investigated these interactions in relation to membrane fouling (Figure 3) [60,61].

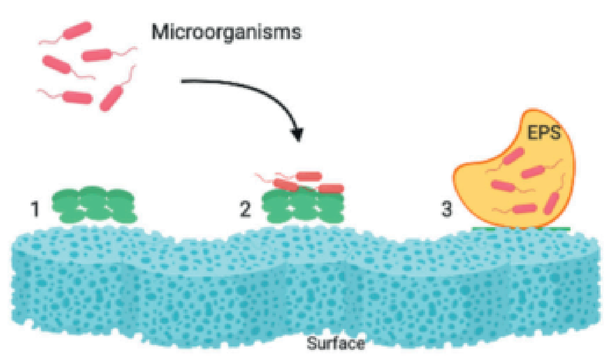

Figure 1: Mechanisms of the biofilm formation: (1) Conditioning film (protein layer), (2) Transport to the surface and immobilization, (3) Attachment to the substrate [59].

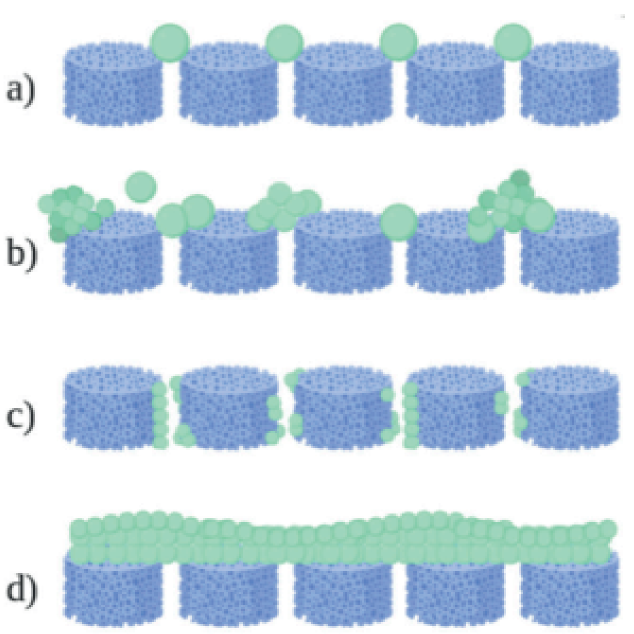

Figure 2: Representation of the fouling mechanisms: (a) complete pore blocking, (b) partial pore blocking, (c) internal pore blocking, and (d) cake formation [59].

In Membrane Bioreactor processes, membrane fouling is a major operational issue, caused by the interaction between the mixed liquor and the membrane.

Three main factors lead to membrane fouling:

i. Gel formation involves the development of a gel-like substance in the membrane pores or on the membrane surface.

ii. Pore plugging, which happens when substances deposit on the surface of the membrane.

iii. Pore narrowing, which occurs when soluble and micro-colloid substances smaller than the membrane pore size are sorbed [62].

Membrane fouling is caused by biofilm, including Extracellular Polymeric Substances (EPS), as well as substances that are soluble, particulate, colloidal, or inorganic [54].

In MBR operation, when a constant Transmembrane Pressure (TMP) is maintained, membrane fouling leads to a decrease in permeate flux. Conversely, when constant permeate flux is maintained, membrane fouling results in an increase in TMP. A significant rise in TMP during continuous flux operation indicates notable membrane fouling. This sudden increase is often referred to as TMP jumps, denoting an abrupt spike in TMP.

Fouling of membranes in MBR process can be divided into three stages [63,9]:

Stage 1: Conditioning Fouling

Conditioning fouling stage due to fast deposition of microbial products residue and initial pore blockage

Stage 2: Gradual Increase in TMP

In this stage, the TMP (transmembrane pressure) shows a gradual linear or weakly exponential increase. This is caused by the formation of biofilm and further blockage of membrane pores.

Stage 3: Rapid Increase in TMP

At Stage 3, the rate of TMP increase (dTMP/dt) increases quickly and drastically [64]. This is caused by the buildup of fouling on the membrane, which is a result of pore closure, shifts in local flux, and a buildup of particles [65-66]. The consistency of the cake layer also changes drastically, and bacteria within the internal biofilm tend to die due to a lack of oxygen, resulting in more extracellular polymeric substances (EPS). When Stage 3 is reached, it is necessary to clean the membrane.

By modifying sludge characteristics, such as MLSS, flock size, EPS content, and apparent viscosity, or by reducing the operational flux, the occurrence of Stage 3 can be delayed and leading to the lower frequency of membrane cleaning and cost savings in MBR operation [54]. Thus, one of the main goals of fouling control is to delay the sudden increase in transmembrane pressure (TMP).

Properties of mixed liquor

Various types of contaminants can be classified according to their biological and chemical properties. These categories are biofoulants, organic foulants, and inorganic foulants.

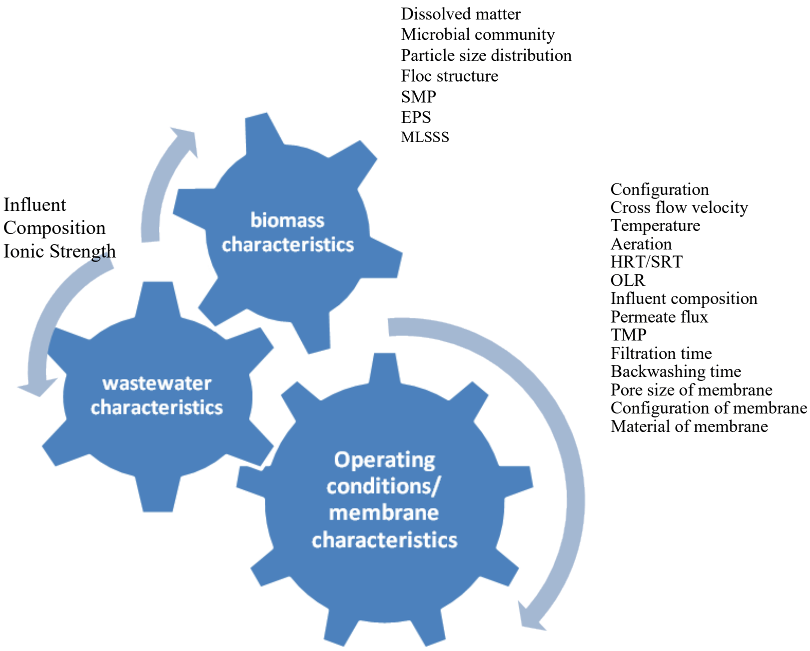

Figure 3: Parameters interacted in fouling of the membrane.

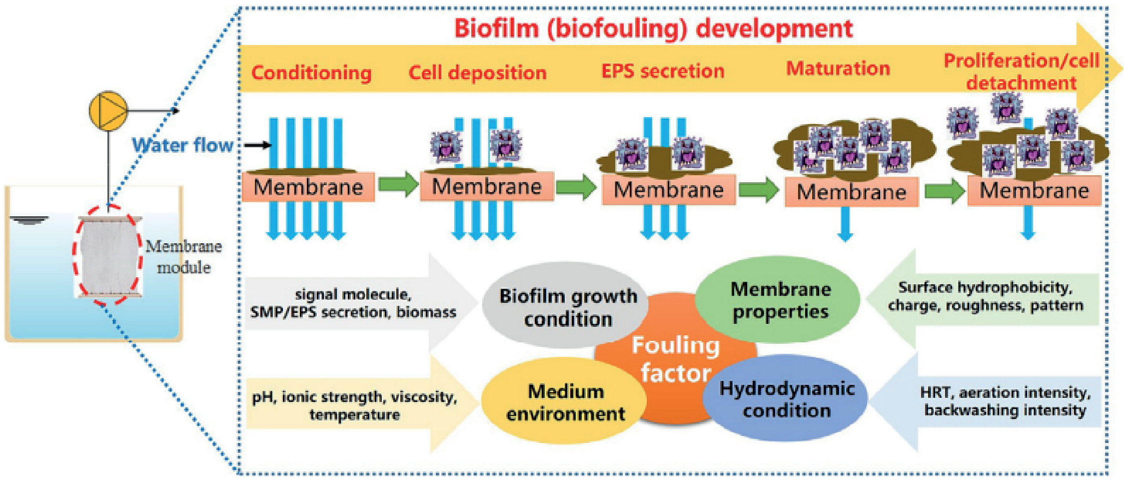

Figure 4: Factors influencing fouling and its step on the membrane.

Organic foulants: Organic foulants, which are biopolymers such as polysaccharides and proteins, are metabolic products of bacteria (known as EPS) that can build up on the membrane in an MBR system and reduce its permeability. A study by Wang XM, et al. [67] showed that these biopolymers can be a major factor in membrane fouling when performing experiments on laboratory-scale submerged MBR with a hollow fiber membrane module.

Inorganic foulants: The precipitation of inorganic ions, such as Ca^{2+}, Mg^{2+}, and Po_4^{3-} onto membrane surfaces and into membrane pores, can cause a process known as membrane fouling. This effect is due to the hydrolysis of these ions, which can lead to changes in pH and oxidation [67].

Biofouling, the fouling of a membrane by microorganisms, occurs due to the contact between the mixture of liquor and the membrane surface. This contact leads to the adherence of microorganisms to the membrane surface, resulting in the formation of a fouling layer known as a "biofilm." The biofilm is composed of a matrix containing microbes and their metabolic products, such as EPS (extracellular polymeric substances) and SMP (soluble microbial products). These substances consist of macromolecules like polysaccharides, proteins, and lipoproteins [68]. The characteristics of the biofilm, including its physicochemical properties, are determined by the microbial cells and EPS present within it [69]. The presence of EPS in the biofilm matrix enables the maintenance of microbial life functions and provides protection to the microbial cells from bio-acids [69].

The development of biofouling can be divided into four steps, as illustrated in figure 2:

1-Attachment of microbial cells to the membrane surface.

2-Secretion of microbial products onto the membrane surface.

3-Production of EPS on the membrane.

4-Growth, multiplication, and eventual detachment of microbial cells from the membrane surface.

The growth of microorganisms/biofilms, physicochemical properties of the membrane, and solution chemistry and hydrodynamic operating conditions are the key factors that significantly impact fouling (Figure 4). Controlling membrane fouling is crucial for the cost-effective and long-term operation of MBR technologies. To prevent fouling and clogging in full-scale MBRs, several strategies are utilized, including:

1-Pre-treating the wastewater before it reaches the membranes,

2-Utilizing permeate backflush/backwashing or relaxation techniques,

3- Cleaning the membranes with chemicals,

4-Using chemically enhanced backwash methods,

5-Scouring the membrane with coarse bubble aeration,

6-Modifying the mixed liquor with chemical treatments.

In MBR systems, the process of reversing the filtration flow is called backflushing. Its main purpose is to remove particles that are attached to the surface of the membrane. During the relaxation time, the filtration process stops to alleviate the pressure on the membrane. Backflushing and relaxation are two periods that occur in the normal operation of MBR systems, so three cycles alternate: filtration, backflushing, and relaxation.

Backwashing/relaxation is a popular technique for eliminating reversible blockages and is especially successful in eliminating cake layers. Submerged MBR systems use coarse bubble aeration in the bottom part of the membrane units to achieve membrane scouring. Chemical cleaning with mineral organic acids, caustic soda, or sodium hypochlorite can be conducted on-site or off-site. Sodium hypochlorite is commonly used to remove biofouling, while citric acid is used to eliminate inorganic fouling. Chemical cleaning is an efficient solution for fouling that cannot be removed during normal MBR procedure, however, regular and intensive chemical cleaning can reduce the life span of the membrane [69-71].

The addition of certain chemicals, such as coagulants, polyelectrolytes, adsorbing agents, and performance enhancers, can modify the characteristics of the mixed liquor to improve the filtration process and reduce membrane fouling. Coagulants are used to introduce positive charges, which neutralize the negative charges of biomass and aid in flocculation. Adsorbents, such as zeolite and activated carbon, have been added to the mixed liquor in MBR systems to reduce fouling by adsorbing colloidal and soluble substances [72]. Adding natural zeolite has been proven to decrease the concentration of soluble microbial products and mitigate fouling [73,74]. While, the addition of a sponge or powdered activated carbon, has been found to reduce cake formation and pore blockage on the membrane's surface [75,76]. Cationic polymers such as MPE50 and poly-aluminum chloride have also been shown to be effective in decreasing membrane fouling [77] (Figure 5).

Biofoulants: Biofoulants are microorganisms or flocks that attach to and accumulate on a membrane surface, which can reduce permeability. This deposition and the metabolic by-products of the microorganisms can cause fouling [78].

Membrane fouling control

Membrane fouling can be caused by combination of foulants particulate, colloidal; mineral scale, nature organic and microbial biofilm, and there are several techniques that can be used to reduce this fouling. The effectiveness of these techniques is dependent on the feed solution and membrane characteristics, and can include boundary layer velocity control, turbulence inducers, membrane material modification, the use of external fields [79], feed pretreatment, flow selection, rotating membranes, and gas sparging [80].

The primary objective of membrane cleaning is to recover the permeation flux, by removing any deposited material from the membrane surface to allow for the movement of permeate. Various approaches can be used to clean a membrane, such as physical, chemical, biological/biochemical, and physico-chemical methods. Cleaning may be carried out either inside the reactor, or with the membrane taken out for separate cleaning. The following cleaning techniques can be employed: ultrasonic cleaning, sponge ball cleaning, chemical cleaning, biological/biochemical cleaning, and physico-chemical cleaning [81,82].

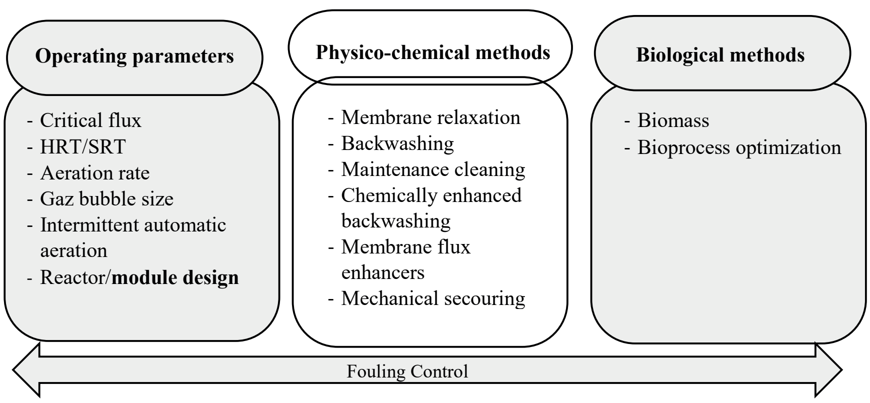

Figure 5: Parameters controlling the fouling of the membrane.

- Ultrasonic cleaning: This method utilizes ultrasound to generate agitation and turbulence on the membrane surface, effectively dislodging foulants and removing them from the membrane [83].

- Sponge ball cleaning is a mechanical method used for membrane cleaning that involves using sponge balls to scrub the surface of the membrane. This technique helps to remove contaminants and other unwanted materials, resulting in a cleaner membrane surface [84,85].

- Chemical cleaning: This method is employed in situations of irreversible fouling. It is crucial to understand the interactions between membrane characteristics and foulants, as well as between foulants and the chemical products used for cleaning, and the compatibility of chemical products with membrane characteristics [86].

- Biological/biochemical cleaning: This cleaning approach utilizes bioactive agents, such as enzymes, to remove foulants from the membrane. Biological and biochemical cleaning methods have a low environmental impact and are commonly used in Membrane Bioreactors (MBRs) [87,88].

- Physicochemical cleaning methods: These methods combine physical and chemical cleaning techniques to enhance the effectiveness of the cleaning process. For example, using ultrasound in conjunction with chemical cleaning can significantly improve flux recovery by up to 95% [89,90].

Membrane-fouling strategies

To reduce and avoid membrane fouling caused by highly concentrated industrial wastewater, a variety of strategies are employed in Membrane Bioreactor (MBR) systems. These involve pretreatment, modifying operational parameters, altering the mixed liquid, and employing advanced membrane modules.

The Pre-treatment is an essential step in controlling fouling as it can lessen the damaging effects of toxic substances or highly concentrated pollutants.

Pretreatment strategies: The success of Membrane Bioreactor (MBR) technology is heavily dependent on effective influent pretreatment [90]. By improving membrane performance, pretreatment can increase the permeate flux and reduce fouling rates. Various techniques are available for pretreatment, including physicochemical methods such as coagulation and adsorption [91]. For example, In 2016, Xue J, et al. [92] discussed the use of ozone pre-treatment for fouling control in an MBR system handling oil sands process affected water. Several strategies are used in Membrane Bioreactor (MBR) systems to control and prevent membrane fouling caused by extreme industrial wastewater. These strategies include pretreatment, operational optimization, mixed liquor adaptation, and the use of novel membrane modules. Pretreatment is an important step because it can reduce the impact of toxic or high-strength pollutants on fouling. Xue J, et al. [92], for example, reported the use of ozone pretreatment for fouling control in an MBR system that manages oil sands process affected water [92]. Also Yu W, et al. [93] conducted an investigation to assess the impact of combining alum and a low amount of NACLP (1mg/l) before UF membrane separation, which significantly reduced membrane fouling rates by nearly 60%. Sardari K, et al. [94] in 2018 applied electrocoagulation as a pretreatment to direct contact membrane distillation (DCMC) and achieved a 57% water recovery rate. Likewise, Unal BO, et al. [95] combined electrocoagulation and electrooxidation procedures in a bioreactor with an electrical membrane, with the aim of improving the efficiency of membrane filtration and successfully managing membrane fouling. In addition, Chang H, et al. [96] and Kong FX, et al. [97] applied chemical coagulation for treating shale gas flowback water and produced water prior to ultrafiltration. These studies achieved decreased membrane fouling and sustained constant flux [97].

As a pretreatment method, prefiltration can involve the use of pack bed filters, strainers, filter cloths, or low-pressure membrane processes. For example, Zavala MAL, et al. [98] in 2014 implemented felt and compressed polyester to treat gray water from washing machines discharges prior to its use.

Some researchers, like Amadou-Yacouba Z, et al. [99], used the preozonation as a pretreatment. Examining the effect of pre-ozonation on fouling during nanofiltration, it was found that when ozonated wastewater from an MBR was used, there was a 62% decrease in flux at 80% of permeate recovery and improved flux recovery after simple water cleaning. Thus, pre-ozonation of the effluent has two advantages: it reduces the need for chemical cleaning and extends the membrane lifetime by postponing chemical cleaning.

In the same vein, Pramanik BK, et al. [100] studied the importance of coagulation as a pretreatment, MIEX (magnetic ion exchange resin), and BAC (biological activated carbon) before the MBR system for controlling the organic fouling of a microfiltration membrane, the results demonstrate that pretreatment with MIEX (Magnetic Ion Exchange) was more effective than pre-coagulation in reducing the fouling of a microfiltration membrane caused by secondary effluent. This is likely due to a greater removal of humic substances achieved with MIEX. All these pretreatment methods are efficient in removal of suspended solids and organic contaminants that cause membrane fouling abilities.

Optimizing of operational parameters: Considering the operating parameters of the MBRs that affect the membrane foulants, significant research work on the MBR process to reduce membrane fouling has been carried out, including contradictory conclusions or shortcomings. Previous research conducted by Banti DC, et al. [101] explained that the significance of filamentous bacteria in the control of membrane fouling was emphasized. Nonetheless, the lower adsorption rate of soluble components by filamentous bacteria results in their diminished population in wastewater treatment processes. This reduction occurs due to the comparatively faster adsorption rate exhibited by other bacteria involved in floc formation. The step-aeration process is designed to alter biological treatment parameters deliberately, aiming to decrease the adsorption rate of floc-forming bacteria. This intentional adjustment fosters a favorable environment for the growth and development of filamentous bacteria.

Also authors highlights the effectiveness of the intermittent or cyclic aeration as a highly efficient method for controlling this technique is commonly employed for treating both municipal and industrial wastewater [102].

Minimizing membrane fouling in membrane bioreactors (MBRs) is achievable through the optimization of operational settings parameters, an illustrative example of this approach is the identification of cyclic aeration as an efficient and energy-conscious method for controlling fouling in full-scale municipal and industrial MBRs [103]. Furthermore, controlling fouling in MBRs requires a thorough understanding of the unique fouling behavior and composition, particular in relation to the specific characteristics of the wastewater.

Modification of mixed liquor: Saline wastewater is difficult to change through pretreatment, changing the mixed liquor is a direct way to reduce the risk of membrane fouling. This modification is achieved by adding biomass media, coagulants adsorbing agents, or other chemicals. For example, Song W, et al. [104] studied two types of carriers in MBR to rebuild the polymeric structure of disintegrated sludge (due to salinity), leading to improved treatment performance in mariculture wastewater and a decrease in membrane fouling.

Membrane Module: Deowan SA, et al. [105] developed a new antifouling coating for MBR membranes using a Polymerizable Bicontinuous Microemulsion (PBM) technique, resulting in a better performance in terms of fouling. Additionally, Zhao C, et al. [106] formulated a new membrane composition by blending Polyvinylidene Fluoride (PVDF) and hydrophilic Graphene Oxide (GO) nanosheets. This new membrane showed superior results when tested in an MBR system, as it demonstrated a higher critical flux, lower cleaning frequency, and lower membrane resistance compared to a conventional membrane.

Energy Consumption in Membrane Bioreactor Technology

One of the drawbacks of membrane bioreactors is the amount of energy they consume. When fouling occurs, the resistance to water flow through the membrane increases. This increased resistance requires higher transmembrane pressure to maintain the desired flow rate, and additional energy is often needed to overcome this resistance. In particular, more energy may be required for air scouring, which is a common method used to clean or prevent fouling on the membrane surface.

Studies have found that, in MBR operations, the average specific energy requirement is typically between 0.6-2.3 kWh/m^3 of treated effluent. Moreover, Novotny V, et al. and Brepols C, et al. [107,108] investigated that in optimal operating and in large MBR plant, the specific energy requirement can be reduced to as low as 0.4 kWh/m^3.

It is essential to reduce the energy consumption of MBRs in order to promote their widespread use. Aeration control based on the real-time analysis of various process parameters can lead to a decrease in the amount of energy needed [109]. Studies have demonstrated positive outcomes, including a 20% decrease in aeration and a 4% reduction in energy consumption, through the use of an ammonia-N-based aeration control strategy in full-scale MBRs [110].

Artificial Intelligence to Control Membrane Fouling

Several research projects have tried to improve operating parameters to decrease membrane soiling by utilizing Artificial Intelligence (AI) and Machine Learning (ML), two effective methods that have achieved excellent results in dealing with such ecological engineering issues [111].

Optimization algorithms are other intelligent techniques that are highly advantageous for better and more efficient membrane fouling control. More research is needed to measure the effectiveness of the above-mentioned intelligent approaches in the case of membrane fouling.

AI-based solutions are increasingly used in the prediction of membrane fouling in diverse membrane filtering systems with complicated and unpredictable systems. Due to their autonomous learning and self-diagnosis capabilities, numerous AI algorithms have been used to predict membrane fouling [112]. However, a critical evaluation of the use of various AI-based algorithms in predicting membrane fouling for various membrane filtering systems is lacking [113].

Conclusion

All industries must deal with wastewater, especially in developing nations, where significant quantities of wastewater are often discharged directly into natural ecosystems without prior treatment. In contrast, most developed countries utilize various treatment methods to eliminate pollutants from the generated wastewater before release. There is an endless list of applications for membrane bioreactor technology for the treatment of various industrial wastewaters, and water pollution has become a serious environmental concern, especially in due to the current water shortage.

This paper offers comprehensive overview of membrane fouling and advances in fouling reduction strategies in MBRs. It covers basic information on membrane fouling and the classes of membrane fouling in MBRs, as well as factors that affect membrane fouling. It also reviews current research trends in the control of membrane fouling in MBRs and highlights successful applications of MBR in treating high-strength industrial effluent. Finally, it addresses the major problem with this innovative technology and how to address it.

The parameters that influence membrane fouling's, such as membrane properties, biomass characteristics, operating parameters, were revealed. The primordial role of membrane fouling strategies in order to prevent fouling and the energy consumption needed while using MBR were also defined and discussed.

Furthermore, the paper examined the utilization of modeling and optimization methods in conjunction with other AI and ML approaches, including cluster analysis, image identification, and feature selection, to effectively supervise and regulate membrane fouling. Hopefully, this review will be useful in providing more information about membrane fouling and membrane technology in general.

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