International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 5, 2025
https://theaspd.com/index.php

Waste Water Treatment Using Membrane Bioreactor: A Brief Review

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Abstract
The exponential rise in human population has fueled expansion in a wide range of industries. Today, a reliable water supply and the ability to process wastewater efficiently to generate high-quality wastewater are considered necessities. By removing both organic and inorganic particles, membrane bioreactors (MBRs), a biological unit for wastewater treatment, can be used to simultaneously address these two urgent issues. MBR facilities have several advantages over more conventional methods like activated sludge because of the combination of the biological process with membrane filtration. They are widely employed in the industrial and municipal wastewater treatment industries. We'll go through the fundamentals of MBR plants in this survey, from their core ideas to the most recent advancements in each component. After thoroughly investigating the features of the bioreactor treatment process, the parameters of the membrane separation procedure are investigated. Both the fouling phenomenon and modern methods for reducing fouling are presented in detail. Fouling is a serious problem that prevents MBRs from being used more frequently. Efforts from a variety of innovative MBR processes are summarised. Issues that now exist and future research projects that could help make MBRs more practically applicable on a larger scale are proposed.
Keywords: *Membrane bioreactor, wastewater treatment, water purification, biological treatment membrane separation, membrane fouling.*

1. INTRODUCTION

Membrane bioreactors (MBRs) are an established method for purifying water and wastewater, and with good reason. Research on MBR is ongoing to make it more reliable and effective for handling different strength levels and wastewater chemical types. This system combines filtration and biological treatment, however occasionally chemicals are added to improve its functionality. Since General Motors finished the first major MBR installation in the United States at its site in Mansfield, Ohio, in the early 1990s [1], researchers in the industrial sector have thoroughly researched the usefulness of MBR. In North America, the first major internal MBR system was installed in 1998 [2], and it was used to clean up wastewater from the food processing industry. Due to the challenges in getting the membrane and the expensive system capital and operating expenses, research on MBR has decreased. When compared to other MBR variations, submerged MBR was shown to have lower operational expenses [3] and was commercialised in the 1990s. In an MBR, biological activities in which wastewater particles are converted into end products before filtering by the membrane is complete play a more significant role than filtration processes. The classic activated sludge (CAS) treatment, which removes the clarifier and replaces it with a membrane to address the settleability problem that occurs when undesired biomass forms, is also recognised as an alternative to MBR. MBR can perform well in the treatment of water and has a smaller environmental impact than traditional activated sludge, which still employs clarifiers. Furthermore, MBR generates less sludge [3, 5], produces high-quality effluent [5, 6], effectively removes organic and inorganic pollutants [6, 7], and can withstand substantial organic loading [6]. Despite MBRs' many benefits, some businesses still opt to install them in order to cut down on water costs and put the treated water to better use. The purified water has many potential applications, including industrial sanitation needs and landscaping. While high-quality MBR treated water can be reused for heat integration and processing, strict monitoring is required to ensure that no contaminants are left behind to damage expensive machinery or block pipes [7]. Membrane fouling is a major problem that is still being studied [8-11], along with the high costs of MBR. The limitations imposed by pH, temperature, pressure, and some corrosive substances are further causes for concern [3, 7, 12]. The membrane is damaged and the reactor's microbes are polluted when fouling occurs. However, some research [13-16] has shown that membrane life can be prolonged. To reduce the restrictions, some studies have recently modified and integrated MBR [15–17]. Reduced biofouling, lower energy consumption, and optimal conditions for MBR operation in the presence of high-strength industrial wastewater and a high shock loading rate are just a few of the benefits of using MBR in an industrial setting. Fouling caused by EPS, SMP, and inorganic compounds has recently taken centre stage in MBR research. Unfortunately, little research has been done on how highly concentrated industrial effluent can cause fouling. This information can be used to enhance MBR's performance in several sectors. This paper looks at the behaviour of the membrane and the biomass, MBR restriction, mitigation, and their link to the widespread use of MBR in the treatment of high strength industrial wastewater.

1.1 A look back at MBR's past

As part of the Dorr-Oliver research programme, Smith initially presented an analysis of MBR technology in 1969. The goal was to use high equality effluent to cleanse sewage from a manufacturing facility for six months at Sandy Hook, Connecticut, in the United States. To separate treated water and activated sludge, an ultrafiltration membrane was put outside the bioreactor tank in place of a sedimentation tank. Despite producing extremely high-quality effluent, the arrangement's utilisation was limited at the time due to high energy expenditures and membrane fouling [18].To overcome the problem with the previous configuration [19]. Since the immersed MBR design was created in the mid-1990s, several research have been done to promote the widespread use of MBR technology through the mass production of high-quality permeate at lower initial investment. Researchers are examining how the module form, pore size arrangement, and process parameters relate to membrane fouling phenomena in order to lessen them and propose cutting-edge techniques for cleaning fouled membranes [20].

1.2 A comparison of CAS and MBR

The right way to make activated sludge (CAS) is a two-step process. Live microorganisms placed in an aerated tank are one approach for treating wastewater (i.e., activated sludge). Sedimentation tank (or secondary clarifier) separates treated water from active sludge. When processing activated sludge, it is necessary to process both the heavier and lighter fractions separately because it is not always possible to entirely separate them in the sedimentation tank. Instead, MBR may filter out the majority of the activated sludge. The advantages and disadvantages of MBR and CAS are summarised for your review in Table 1 [21]. Refer to Table 2 for details. This review will begin by introducing the reader to the fundamental concepts underlying MBR, and will then go on to discuss the most recent advancements in each component of MBR plants, such as fouling reduction, which is crucial to the success of MBRs. This primer begins with an introduction to membrane technology and biological wastewater treatment. The sections that follow highlight and investigate fouling phenomena, ranging from the most fundamental to cutting-edge fouling mitigation techniques that have recently been used. Following that, a study of innovative configurations is presented to provide a thorough grasp of current advancements in MBRs. This discussion is based on the results of recent scientific investigations into the issue. Last but not least, the challenges that must be overcome in order to advance MBR technology are laid out.

2. Biological Waste Water Treatment

Table I MBR's benefits and drawbacks in comparison to CAS [21].

Benefits	Drawabacks
By measuring the amount of time a solid stays in a bioreactor's MLSS, we may get a sense of how well the device performs as a therapy tool (SRT). Now that the secondary sedimentation tank has been taken out, the MBR can carry out fine SRT control. The procedures for maintaining and cleaning the membrane are mostly to blame for the procedure's complexity.	The procedures for maintaining and caring for the membrane are primarily responsible for the methodology's complexity.
Membrane porosity allowed for the generation of superior treated effluent. The MLSS of the bioreactor and the quality of the treated water can both be evaluated using the solid retention time (SRT). Size is greater than that of suspended solids. On the other hand, effective secondary clarifiers	Increased energy consumption while operating. At times, it is twice as much as the CAS's electrical use.

typically have SSs concentrations of roughly 5 mg/L. Tertiary treatment, like as filters in MBR, is unnecessary.	
Reduced footprint as a result of the elimination of the sedimentation tank and smaller bioreactor.	Fouling is a common issue with MBRs, and regardless of the membrane installation method or complexity, there are a variety of operating methods that may be performed to lessen the membrane's inclination to foul.
Longer SRT often increases wastewater effectiveness. In MBR, SRT applications lasting longer than 20 days result in better effluent quality than CAS (typically 5-15 days).	Additionally, MBR's increased aeration need exacerbates the issue of high foaming tendency.

Table II Reduce membrane fouling phenomena during MBR plants wastewater

New strategy	Fouling retardation performance	Brief result	Reference
Altering the biomass's characteristics	By using nanoparticles as adsorbents, MBR effectiveness and fouling properties are evaluated. (Comparison of the magnetic component Fe_3O_4-NP and the antibacterial substance Ag-NP, generally known as NP1 and NP2, in MBR plants.)	NP1 outperforms the original system in terms of EPS and SMP removal due to NPs' ability to adsorb organic compounds, enhancing COD elimination in both systems. (The EPS and SMP of NP1 were lowered by 49% and 66%, respectively, compared to 38% and 54% for NP2.) increased NP2 flux rate by 32% and 41%, respectively.	[114]
Improving Operating Conditions	Examining the impact of temperature on An-methanogenic MBR's activity	Reduced energy requirement as a result of decreased liquid viscosity brought on by a drop in temperature lowering the temperature in two MBR plants that were running at 15 and 25 degrees to limit methanogenic activity boosting flux while lowering the temperature.	[115]
Mechanical cleaning	Basic and thorough analysis of mechanical cleaning in MBR plants that uses scouring agents that are both porous and non-porous to control fouling.	Reducing the number of cleaning cycles or gas sparging energy requirements. Agent diffusion through the laminar boundary layer generated by the membrane's surface	[116]

		provides for a high level of control and is a highly effective way of fouling control. With the use of scouring chemicals, the membrane can be completely stripped of all cake layers. The removal of the cake layer is, however, causing more persistent fouling.	
Activated sludge change	Adding a flux enhancer prevents fouling. However, depending on the kind of sludge, the specific dosage of FE varies substantially. (Seven samples of An-MBR sludge from industrial wastewater treatment were treated with a cationic polymer called Adifloc KD451 as a FE.)	Dosages of optimal and critical FE vary widely among samples. DOPT concentrations might be anywhere from 0.02-1.16 g/l, and DCrit concentrations could be anywhere from 0.1-2.5 g/l. Furthermore, a linear association between DOPT, capillary suction time, and SMP-PS was found employing the Anaerobic Delf Filtration Characterization method (AnDFCm). Overly high levels of FE are counterproductive in preventing membrane fouling. Using existing sludge samples to power empirical models for estimating FE dosing for a fresh sample.	[117]
Membrane structure modification	To enhance photocatalytic activity, the metal-organic framework membrane was modified. (In a practical anammox membrane bioreactor (MBR), PVDF membrane-integrated CdS/MIL101 (Cr) is used as a visible light photocatalyst by means of	Higher antifouling characteristics, a slower rate of flux decrease, higher fouling rejection, a smaller increase in TMP, and decreased membrane fouling over time are all advantages of manufactured membrane over original membrane. Both membranes remove nitrogen in a similar way.	[118]

	submersible, waterproof lamps.)		
Hydrophilic membrane surface modification	Because Anammox's hydrophilic modification showed promise in both aerobic and anaerobic MBRs, its antifouling efficiency was assessed. Using a polyvinyl alcohol solution, vintage nylon cloth meshes can be coated to create a hydrophilic membrane (Mh) ancient nylon fabric meshes were coated with polyvinyl alcohol solution (Mp).	Mh has a stronger gel layer than Mp does. On Mh, a tiny, compact gel layer was created, whereas on Mp, it was thick and loose. Anammox MBRs' long-term functioning involves brief filtration cycles with rapid flux reduction heterotrophic bacteria to autotrophic bacteria in anammox MBR plants.	[119]
Making changes to activated sludge	Adding a flux enhancer to cut down on fouling However, the precise amount of FE needed varies greatly amongst the various sludge varieties. Seven An-MBR sludge samples were treated with Adifloc KD451 cationic polymer as a FE.	The optimal and critical FE dosages differ significantly between samples. (The DOPT ranged from 0.02-1.16 g/l, while the DCrit ranged from 0.1-2.5 g/l.). The association between DOPT, SMP-PS and capillary suction time is linear.	[117]
Preparing the feed	To reduce membrane fouling, advanced oxidation was utilised as a pretreatment, and the results were compared to those obtained utilising the coagulation strategy. To avoid fouling, a ceramic MF membrane was pretreated with UV/H_2O_2 and coagulated with aluminium chloralhydrate.	Both methods have the ability to lessen the resistance to fouling. primarily because of biopolymer degradation at extremely high MW. The amount of irreversible fouling created by the coagulation method is less as compared to the advanced oxidation process. A substance with a lower melting point was created when UV/H_2O_2 was used	[34]

		[A.S. Ziegler, et al., 26][34].	

Size, filamentous microbe content, growth rate, and other characteristics of the microorganism. On the other hand, the performance of the MBR can be impacted by the activity of microorganisms in two separate ways: the effluent quality, the MBR's capacity to handle wastewater contaminants and the membranes' propensity for fouling. It is therefore crucial to have a solid grasp of the fundamentals of biological wastewater treatment, such as microbiology, microbial metabolism, Bioreactors' optimal operating parameters are determined with the use of microbial stoichiometry and kinetics [22]. For a specific MBR unit, the structure and microbial community's composition varies over time and from one MBR plant to another. This distinction is mostly due to the crucial characteristics of microorganisms in MBR plants and other environmental engineering systems. Different populations of microorganisms form in the bioreaction as a result of the atmospheric wastewater that is fed into it. However, a certain type of microorganism can be enhanced in the bioreactor by altering the operating parameters and reactor design [10][23]. Both CAS and MBR plants use the same kind of microbe and they both function in the same way.

However, MBR bioreactors have unique qualities because of their prolonged SRT and high biomass concentration, as demonstrated in Ref. [24]: 1. Longer SRTs of CAS aeration tanks sustain slow-growing microbes, which is advantageous because it speeds up the breakdown of resistant organic waste. Additionally, it can 1. Increase the production of inert solids, which lowers the bioreactor's active biomass to total solids ratio, and 2. create unwanted bacteria, such as foamy microorganisms.

2.1. Type of microorganisms

Metazoa (including rotifers, worms, and tardigrades), filamentous bacteria (including protozoa), amoebas, flagellates, ciliates, and fungi are the five main types of microbes that are frequently present in bioreactors [25]. However, bacteria make up more than 90% of the microorganisms in activated sludge [25]. Most bacteria live in colonies of two, three, or more, however other strains can only exist as single cells. Their metabolisms are flexible, allowing them to make use of various forms of carbon, electron donors, and electron acceptors. Their versatility means they can be used to treat a wide variety of wastewater problems, from neutralising organic and inorganic pollutants to preparing the soil for the extraction of individual substances. Sequencing 16S rRNA genes, Shchegolkova et al. [26] analysed bacterial communities in activated sludge and incoming sewage from three separate wastewater treatment plants. The top 40 bacterial families in AS are shown graphically (they account for between 94.2 and 97.5% of all bacteria; see [27] for details). A biofilm develops when bacteria with a propensity to congregate on membrane surfaces. Biofilm cells ensconce themselves in a matrix comprised of their own extracellular polymeric substance, as opposed to planktonic cells (EPS). Biofilm development is a frequent issue with MBR plants since EPS contains proteins and carbs [27].

2.2. Stoichiometry and kinetics of microorganisms in bioreactors

Similar to chemical stoichiometric equations, balanced microbiological stoichiometric equations are crucial for predicting biological performance and the efficacy of treatments. However, the consumed substrate is used both as an energy source and for biomass synthesis in the kinetics equation for microbes. In other words, bacteria are used to self-replicate through microbial growth in addition to serving as catalysts for biological reactions. "Biomass yield" or "growth" refers to the ratio of biomass production to substrate consumption, such as glucose [26]. Bioreactor performance (including biomass generation rate and effluent substrate concentration) and design parameters can be calculated using microbial kinetics and mass balance models (volume). Substrate utilisation and microbial growth rate are the most important aspects of microbial kinetics [28]. In general, when microbial populations grow, they tend to degrade. For each system, the "net growth rate" is calculated by adding the expansion rate to the contraction rate.

$R_{g,net} = R_{decay} + R_{growth}$ (1)

$R_{g,net} = dX/dt + \mu_m SX / K_S + S - k_d X$ (2) $R_{g,net}$ denotes the net growth rate (g VSS/m^3:day), X the biomass concentration (g VSS/m^3), and S the biodegradable substrate concentration (g COD/m^3). μ_m represents the maximal specific growth rate (day $^{-1}$). The half saturation constant for biodegradable substrate (g COD/ m^3) and the decay coefficient (g VSS/ g VSS. day) are represented independently by K_S and k_d [29].

Table III: Advantages and disadvantages of various polymers, including their production methods [8].

Polymer	Fabrication	Advantage	Disadvantage
PVDF	NIPS, TIPS	Excellent mechanical qualities, excessive fracture elongation Limited Chemical resistance and uniform pore size distribution.	Poor performance under normal circumstances, therefore it is challenging to build a structure.
PE	MSCS	Ductile, economical	Extra-large pores
PTFE	MSCS	Minimal likelihood of clogging, good water permeability, excellent chemical	Large total cost , design for tough fabrication
PSF	NIPS	Protected from leaking Excellent mechanical toughness	Low chemical resistance stiff or fragile
PVC	MSCS	Affordable, Ductile	Extra-large pores, not robust enough to handle simple situations

Wastewater is cleaned because microbes consume biodegradable contaminants, or substrate, as their food supply to thrive. Engineers place more importance on substrate removal rate than microbial growth rate, as the former indicates how well the treatment is working [28]. It is also crucial to note that a key factor in designing and operating bioreactor facilities is the rate at which VSS is produced in the bioreactor. Three main factors contribute to the formation of VSSs in a bioreactor's mixed liquor: microbial growth, biomass decay that produces nonbiodegradable VSSs that microorganisms cannot use as their substrates, and, lastly, influent wastewater that, based on wastewater parameters, results in nonbiodegradable VSSs. Therefore, the following can be said about the whole VSS production rate ($R_{VSS,t}$):

$R_{vss,t} = \mu_m SX/\ K_S + S - k_d X + f_d k_d X + X_0 Q/\ V$ (3), where f_d is the proportion of biomass decay products that accumulate in a bioreactor. X_0 denotes the concentration of nonbiodegradable VSS in wastewater influent (g VSS/m^3); Q and V denote the influent flow rate (m^3/day) and bioreactor volume (m^3), respectively.

3. Membrane separation process

3.1 Membrane material

There is no strict rule on what can or cannot be utilised to make a membrane. However, there are only a limited quantity of them available for purchase. High acidic, basic, chemical, and mechanical resistance for five years of operation, as well as the ability to withstand exposure to a wide pH range of 1 to 12 (during operation and recovery) [30] are required for membrane wastewater treatment applications. These specifications can be met by membranes made from a variety of materials, including plastics, ceramics, and even stainless steel. Polymers are widely utilised in membranes that filter water and wastewater. The most widely utilised polymers nowadays are polysulfones (PSFs), polyvinylidenedifluoride (PVDF), polytetrafluoroethylene (PTFE), and cellulose acetate (CA) [22][30]. Table 3 provides a concise summary of the characteristics of common polymer-based materials used to produce membranes.

3.2 Manufacturing methods for membranes

Many different methods exist for the fabrication of membranes. This article discusses three of the most common methods for producing membranes: non-solvent induced phase separation (NIPS), melt spinning and cold stretching (MSCS), and thermal induced phase separation (TIPS).

3.2.1 NIPS

Polymers solubility in various solvents varies, making this membrane-forming technique the most favoured. This method employs two appropriate solvents, each of which has a different level of polymer solubility. A "good solvent" or "nonsolvent" is one in which the polymer is just little soluble, whereas a "excellent solvent" is one in which it is very soluble [31].The appropriate solvent is first combined with the polymer before the production process begins. An injection needle is then used to inject the prepared solution into the inadequate solvent. As the appropriate solvent permeates into the inadequate solvent, the polymer becomes rigid (or gels). Due to the diffusion of an excellent solvent into a solution containing a poor solvent, holes emerge and grow on the membrane structure. Figure 1 depicts the concept for the NIPS fabrication procedure. In order to get rid of any leftover good solvent, bad solvent solution, or additives, washing and drying the polymer is the next step. Polymer composition, solvent quality, injection nuzzle shape and size, and other factors are used to regulate the pore diameters of the inner and outer membranes in this method [31].

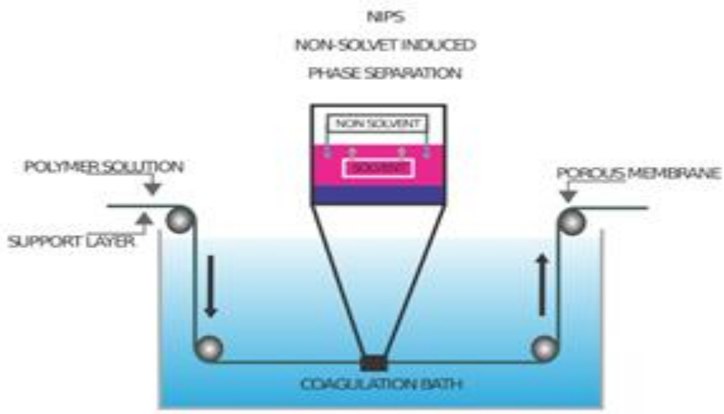

Figure I. Representation of NIPS fabrication process

3.2.2. MSCS

Polymers typically have two distinct structures. The flexible section is an amorphous interlamellar structure, whereas the traditional arrangement is a crystalline lamellar structure. There are so two transition temperatures for polymers. Amorphous structures become active above glass temperature (Tg), while crystalline structures are active above the melting temperature (Tm) (usually Tm is higher than Tg). First, the polymer is melted in the manufacture of membranes using the MSCS process. The material is then stretched in one or both directions while being cooled to slightly below the Tm. In this method, the crystalline geometry is maintained while the amorphous structure expands and generates pores of varying sizes. This method yields the cheapest membrane, but it has significant drawbacks, such as a large average pore size and the inability to modify the membrane's pore size distribution [32].

3.2.3. TIPS

This method of membrane generation was based on changes in solubility and melting temperature. TIPS, in other words, is a hybrid of the two aforementioned approaches. By adding solvents or diluents at high temperatures, polymers are dissolved or diluted. After that, it was quickly cooled by cold liquid to get rid of any leftover solvent or diluent and create membrane holes. On occasion, the stretching process for membranes is used to increase their mechanical strength. However, one of the main issues with this technique is the weakness of the manufactured membrane, which has drawn a lot of attention in an effort to solve the problem [33].

3.3. Membrane characterization

3.3.1. Membrane components

The most common membrane shapes are hollow fibre, tubular, and flat sheet. For hollow fibre and tubular membranes, the outer diameter, inner diameter, and membrane length are key characteristics, but for flat sheet membranes, the thickness, length, and width are crucial criteria. The hollow fibre membrane is divided into two types based on its diameter [3]. All dimensions can be measured precisely using micrometres, callipers, or a field emission scanning electron microscope (FE-SEM). Their primary drawback is that they require frequent washing to prevent fouling [26]. Tubular membranes are ideal because of their high mechanical strength, low fouling rate, long lifespan, and simple cleaning and maintenance. They are not widely employed, however, due to their low packing density and expensive capital and operating costs [34].

3.3.2. Pore size distribution

Both permeable and impermeable membranes are commonly employed in wastewater treatment. Potential factors in membrane fouling include wastewater particle size and membrane pore size. With larger pores, more particles can get through, but smaller particles are more likely to become trapped in the membrane. Despite having smaller hole diameters, tiny particles can still accumulate on the layer generated by larger particles on the membrane. Several methods, including air scouring, can be used to readily remove this generated layer. Measuring FE-SEM pictures of the membrane's surface can offer information about the material's pore size distribution. It is impossible to establish the full pore size distribution of the membrane from the generated image since it only represents a small portion of the membrane surface [35].

3.3.3. Hydrophilicity

The membrane's hydrophilicity has a substantial effect on its fouling propensity. Hydrophilicity is the attribute that describes how much water a membrane can absorb. The majority of polymer-based polymers are hydrophobic, and their fundamental disadvantage is a significant fouling tendency. Biomass in the form of hydrophobic organic molecules and activated sludge floc are produced by microorganisms in the MBR. The membrane's hydrophilicity can be increased by including specific hydrophilic components during manufacturing [28]. Additionally, wetting chemicals are employed to increase water permeability so that water can enter the membrane pores. Average pore size, water surface tension, and contact angle all have an impact on minimum hydraulic pressure [36].

3.3.4. Electric charge (Zeta potential)

Both the hydrophilicity and the fouling tendency of a membrane's surface could be influenced by its electric charge. To foul MF and UF membranes, the most common types employed in MBR, organic molecules with a negative surface charge are most often the culprits. Because of this, membranes with a higher negative surface charge are less likely to foul [37]. The zeta potential is a measurement of a membrane's surface charge. Sedimentation potential characteristics, electroosmosis, and electrophoresis are additional techniques that may be utilised [37].

3.3.5. Surface roughness

Foulants can make significant contact with the membrane's surface thanks to its rough surface. As a result, fouling is more likely when a membrane surface is more abrasive [38]. Atomic force microscopes (AFMs), a type of scanning probe microscope (SPM) [39] can be used to measure the roughness of a membrane. AFM research of membrane surface roughness has determined that membranes with larger pore sizes have rougher surfaces than those with lower pore sizes. Furthermore, the fouling rate directly correlates with surface roughness, increasing as surface roughness increases [39].

4. Membrane Fouling in MBR:

The International Union of Pure and Applied Chemistry (IUPAC) Working Party on Membrane Nomenclatures defines membrane fouling as "the system leading in the deterioration of a membrane's effectiveness as a result of hanging or dissolved substances on its outer surface, at its pore entrances, or inside its pores" [44].These foulants in the MLSS could be solutes, colloids, or suspended particles (microorganisms and cell debris) [40, 42, 43]. Membrane fouling is brought on by a physicochemical reaction between foulants and membrane components. An MBR's inability to treat the required design flows due to improper membrane fouling control is possible [41]. The membrane develops a layer (biocake) as a result of the buildup of microbial communities, biopolymers, and inorganic debris [45]. Membrane filtration is less effective because of the cake layer. Membrane fouling reduces permeate flux and increases transmembrane pressure when the MBR is run at a constant TMP (TMP). If the TMP suddenly increases during continuous flux operation, then there is likely to be significant membrane fouling. A "TMP leap" describes this unexpected increase in TMP. In the first stage of fouling, pore blocking and solute adsorption occur; in the second stage, TMP gradually increases as biofilms grow and more membrane pores become blocked; and in the third stage, the rate at which TMP increases (dTMP/dt) increases sharply and suddenly. Particle deposition acceleration [47, 48] and sudden changes in the structure of the cake layer [46] are attributed to fouling's pore closure and local flow alteration. This is stage 3 membrane fouling. EPS synthesis increases as a result of oxygen deprivation, which kills bacteria within the biofilm [49]. Once step 3 is complete, the membranes need to be cleaned. The result

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 5, 2025
https://theaspd.com/index.php

of this is a delay in the show. The amount of money spent operating the MBR will decrease if the membrane doesn't need to be cleaned as frequently each year. Changing the properties of the sludge is an important part of fouling control since it can reduce operational flow or delay TMP jump (MLSS, floc size, EPS concentration, and apparent viscosity). 2016 saw a drop in membrane costs across all price points by between 6 and 33 percent. Fouling control works to alter sludge characteristics (mean suspended solids [MLSS], floc size, EPS concentration, and apparent viscosity) to slow operating flow or postpone TMP jump [41]

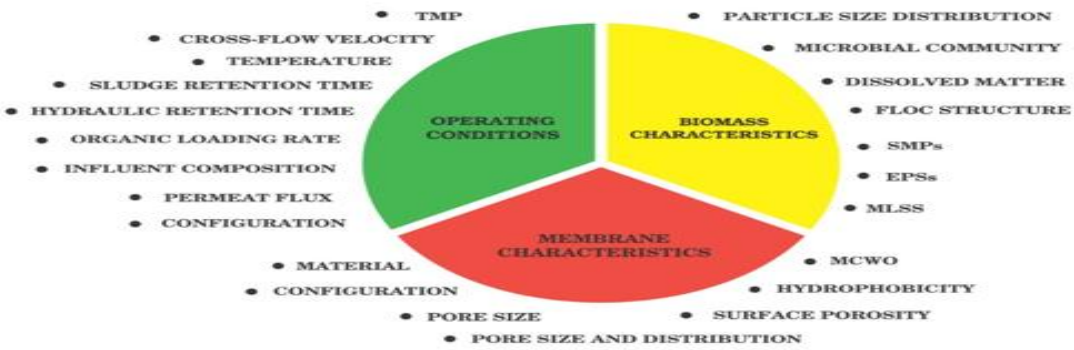

Figure II Effective parameters in membrane fouling

4.1. Forms and Varieties of Foulants

Membrane foulants in MBR can be broken down into three distinct groups based on their biological and chemical properties: biofoulants, organic foulants, and inorganic foulants [50].

4.1.1. Biofoulants

Microorganisms (bacteria or flocs) that cause fouling by depositing on, proliferating, and metabolically modifying a membrane are known as biofoulants [41]. Eventually, the cell multiplies to produce a biocake, which decreases permeability. Bacteria (biofoulants) and the metabolic metabolites of these microorganisms cause fouling [51]. Membrane biofouling typically occurs in two stages, starting with early bacterial adhesion and moving on to bacterial multiplication on the membrane surface [52]. The metabolic waste products produced by these bacterial cell clusters are included in some research [51] that broaden the definition of "biofoulants. The organic chemicals produced by bacteria are referred to as "organic foulants" [53] for the sake of this work's investigation into bacterial mitigation strategies.

4.1.2. Organic Foulants

Organic foulants in MBRs are biopolymers like polysaccharides and proteins that deposit on the membrane and make it less permeable. In an experiment to investigate membrane fouling under different operational settings utilising a laboratory-scale submerged MBR with a hollow-fibre membrane module, Wang and Li observed that biopolymers are large foulants and have a considerable impact on membrane fouling.

In MBR sludge, EPS and biopolymer clusters (BPC), a collection of sizable free organic solutes, have both been identified [55]. Soluble microbial products (SMPs) and free EPS clump together in the sludge cake to create BPCs [56]. Biopolymer concentrates (BPCs) are much larger than microbial mats (SMPs) and are made up almost entirely of biopolymers with only a few bacteria. In contrast to bacterial flocs, BPCs are cleaner. Due to their larger size, BPCs are retained by the membrane in MBRs, hence their effluent does not contain them. Because of the MBR's large membrane surface, BPCs have an ideal habitat in which to grow and multiply, and their presence causes significant harm to the membrane over time [57]. Sun et al. [58] conducted an experiment to ascertain the fouling propensity of MBR sludge and found that an increase in BPC content in the mixed sludge liquid by 20% and 60% from around 3.5 mg/L resulted in a 120% and a 300% increase in fouling, respectively. Less bacteria are present in BPCs than in bacterial flocs.

4.1.3. Inorganic Foulants

Inorganic foulants cause membrane fouling when they precipitate on or enter the membrane through the holes. They include, but are not limited to, the cations and anions Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}, SO_4^{2-}, PO_4^{3-}, CO_3^{2-}, OH^-, etc. [59,60]. These species precipitate onto the membrane surface [54] due to a change in pH and oxidation caused by hydrolysis. Creation of inorganic species and inorganic-organic complexes is primarily driven by chemical and biological precipitation [36][59]. Ca^{2+} in moderate concentrations (up to 280 mg/L) can be helpful in reducing and improving biofouling by binding and bridging EPS (hence, improved bioflocculation) [38], whereas metal ions in concentrations over 800 mg/L have been shown to significantly increase inorganic fouling due to the high inorganic precipitate content of the MBR mixed liquor [61]. To differentiate it from biofouling and organic fouling, inorganic fouling is also referred to as "mineral scale" [62]. In particle fouling, colloidal particles are transported from the solution to the membrane surface by convection, whereas ions precipitate onto the membrane surface during crystallisation [63].

5. Factors influencing fouling of membranes in MBRs.

5.1. Membrane Characteristics

5.1.1. Membrane Material

The fouling resistance of a membrane and its material are related when MBRs are utilised. The three different types of membranes that can be classified according to their constructional components are composite membranes, polymeric membranes, and ceramic membranes. Excellent chemical resistance, integrity, inertness, and simplicity of cleaning make ceramic membranes an attractive filtration option [41, 64, 65]. The majority of membranes are polymeric. Hydrophobic polymeric membranes provide high physical and chemical stability [5]. Polyvinylidene fluoride (PVDF), polyethersulfone (PES), polyacrylonitrile (PAN), polysulfone (PS), polyethylene (PE), polyvinyl butyral (PVB), cellulose acetate (CA), polypropylene (PP), polytetrafluoroethylene (PTFE), and other polymers are just a few examples of the polymers used in polymeric membrane components. Despite being hydrophobic and rapidly becoming fouled, polymeric membranes are being used increasingly frequently because it is simple to create different pore sizes. Using the greatest features of each component, composite membranes combine many materials into one. Usually, the active surface material and the support layer material are separate. After cleaning the membrane with caustic and water, the flow recovery was 35% higher than it had been before [66]. The alteration of PE is the subject of another study.

PVDF-TiO_2 nanocomposite membranes permeability and antifouling qualities were assessed by Moghadam et al.[68] both with and without UV radiation. When filtration and UV irradiation at 365 nm were coupled, the flux recovery ratio was greatest for PVDF-TiO_2 nanocomposite membranes. Negative effects on ecotoxicology and human health [46][69] may result from exposure to modified membranes, and further research is needed to identify the long-term effects of these membranes.

5.1.2. Attraction to Water

The contact angle of a water droplet on the surface of a membrane material is a reliable indicator of its affinity for water [70]. Larger values indicate a more hydrophobic orientation relative to the hydrophilic. Membrane fouling in hydrophobic membranes is more severe than in hydrophilic membranes [101] due to hydrophobic interactions between the membrane material, microbial cells, and solutes. This is due to the fact that more hydrophilic membrane materials are less likely to absorb wastewater macrosolutes like proteins. In contrast, hydrophobic materials tend to absorb hydrophobic chemicals from wastewater, resulting in fouling.

5.1.3. Surface Roughness of the Membrane

Membrane fouling in MBRs is barely influenced by surface roughness. As opposed to uneven surfaces, membranes with a consistent roughness are less likely to become fouled [70]. Rougher membranes foul more frequently, according to the research [71]. Fouling is worse for rougher membrane surfaces [73] because a rough surface makes a valley where the colloidal particles in the wastewater can settle [72]. Surface roughness and membrane fouling in MBRs [74] research indicated that membranes with more protrusions on the outer surface displayed stronger antifouling capabilities, and the recovery of permeability after backwashing followed a similar trend.

5.1.4. Surface Potential of a Membrane

The presence of charged particles in the feed can affect fouling due to the membrane's surface charge. This is because there is always the risk of colloidal particles accumulating on the membrane's outside, as mentioned in [72]. When positively charged MLSS cations like Ca^{2+} and Al^{3+} come in touch with negatively charged membrane surfaces, a process known as inorganic fouling occurs.

5.1.5. Membrane Pore Size

Wastewater treatment facilities frequently use both porous and non-porous membranes. Shirazi et al. claim that non-porous membranes depend on variations in the solvent's or the solute's solubility or diffusivity [74]. Tight-end and reverse osmosis (RO) systems use non-porous membranes (NF). To physically retain all bacterial flocs and nearly all suspended particles, MBRs typically employ a sieving (size exclusion) separation mechanism, and MF and UF membranes are commonly utilised for this purpose. There may be a correlation between the particle size in the wastewater input stream and the pore size of the membranes when it comes to membrane fouling in MBRs. According to the theory put forward [70], more pore-blocking mechanisms will be needed as membrane pore diameters grow. This is because sub-micron particles can become stuck in the membrane's pores, blocking the passage of fluid [75]. As larger particles accumulate on top of the membrane, they block passage for smaller ones. The film that forms on the membrane can be quickly removed by air scouring or the turbulence created by cross-flow filtration. Fouling in a membrane bioreactor (MBR) was studied by Miyoshi et al. Polyvinylidene difluoride (PVDF), cellulose acetate butyrate (CAB), and polyvinyl butyral (PVBR) membranes were used in these studies (PVB) [76].

5.2.6. Rate of Organic Loading (OLR)

The overall load ratio of any biological wastewater treatment system is among the most crucial factors (OLR) [77]. The effect of constant and variable influent OLR on membrane fouling was investigated by Zhang et al. [78] using two identical submerged MBRs for 162 days at an SRT of 30 days. In this experiment, we compared two MBRs, one of which had its influent OLR held steady and another of which had its OLR altered. Membrane fouling was observed to be more severe in the MBR that had fluctuating OLR compared to the MBR that had constant OLR. At the MBR's steady state, however, the fouling propensity was clearly reversed, and several different feed OLRs displayed much reduced membrane fouling (where the MBR systems eventually stabilised in terms of biomass concentration and TOC removal).

5.2.7 Ratio of Food to Microorganisms (F/M)

When evaluating the efficacy of a biological wastewater treatment system, the F/M ratio is a vital sign of success. Using real city wastewater and three identical pilot-scale MBRs, Kimura et al. [79] studied membrane fouling under a variety of operating conditions. Specifically, the researchers discovered that a higher F/M ratio was associated with higher protein concentrations in foulants [79]. Trussell et al. [80] found that an increase in the F/M ratio accelerates membrane fouling in MBRs. Values of the F/M ratio near to one show that quick consumption of food by biomass may increase EPS production [81].One more investigation found a correlation between low F/M ratios and low EPS levels [82].Therefore, smaller F/M ratio values are preferred for operation.

5.2.8 Liquid Storage Interval for Solids (SRT)

In MBRs, the SRT has a major impact on membrane fouling [13]. The SRT was modified as a result of the introduction of EPS. EPS concentrations decrease as biomass remains in the system for longer, hence EPS levels rise with decreasing SRT and decline with increasing SRT, as shown by numerous studies [83-86]. Reduced EPS synthesis, reduced sludge generation, and nitrification are all outcomes of high SRTs in the bioreactor [88, 87].

6. Types and different MBR setups

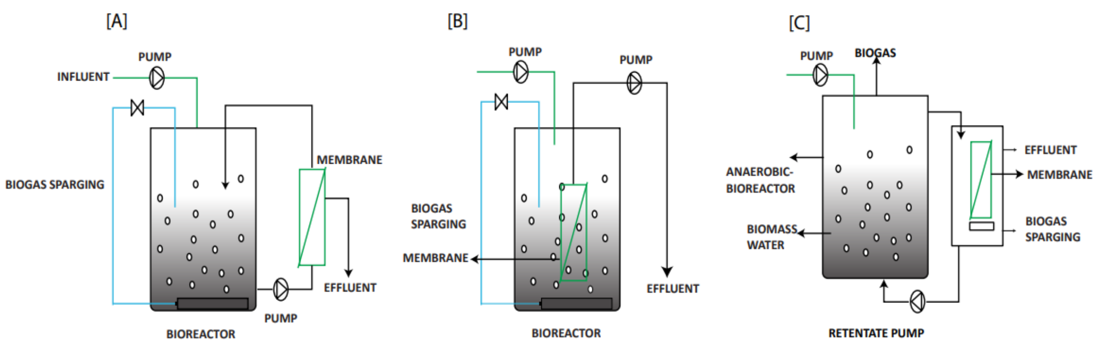

Figure III Basic configurations of anaerobic bioreactors [A] External AnMBR [B] Internal/Submerged AnMBR, And [C] External submerged AnMBR

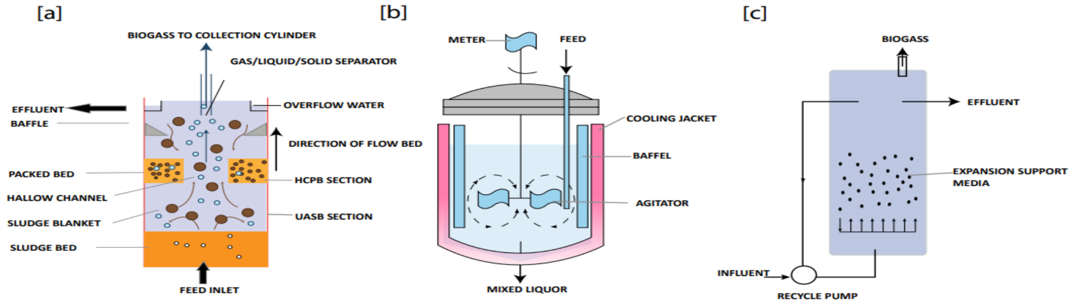

Figure IV Typical anaerobic bioreactors [a] Up-Flow Anaerobic Sludge Reactors [b] Continuous Stirred-Tank Reactor [c] Anaerobic Fluidized Bed Reactor

6.1 Aerobic and anaerobic membrane bioreactor (AnMBR)

Using aerobic treatment technologies, industrial wastewater and effluent have been treated for the past century. Bioreactor with both aerobic and anaerobic membranes (AnMBR). Energy-intensive aeration process, massive amounts of sludge generation, greenhouse gas emissions like nitrous oxide (N_2O), significant environmental impact, and high maintenance costs are only a few of the issues with this method. Aeration control systems in aeration tanks are crucial for expanding the use of aerobic MBR since they reduce the process' overall energy consumption. Large-scale MBRs that use an ammonia-N based aeration management technique have 20% lower aeration rates and 4% lower energy usage [89]. As compared to open loop aeration, close loop aeration that maintains a consistent quantity of dissolved oxygen within the aerobic reactor allegedly reduces the operational expenses of MBR plants by 13–17 percentage points [90]. Anaerobic treatment is a flexible technique that can treat wastewater to recover water, recover nutrients for use in agricultural fertilisers, and produce sustainable fuel (biogas) by decomposing organic materials already present in wastewater [91]. In an alternate MBR design, anaerobic digestion and membrane filtration have been combined to treat wastewater and circumvent certain MBR process limitations. Moreover, the conversion of nutrients into chemically usable forms makes future precipitation possible for nutrient recovery [92]. However, membrane fouling, diluted resources, salinity, and stability must be considered.

Urbanization is one of the primary obstacles to its development [92]. The membrane models and anaerobic bioreactor were the two components of the AnMBR facility. The three most common bioreactor designs for AnMBR are anaerobic fluidized bed bioreactors (AFBRs), fully stirred tank reactors (CSTRs), and up-flow anaerobic sludge blankets (UASBs) (Fig. IV). Due to its simplicity of usage and construction, the CSTR is the most often used structure. In Figure 6 we see three distinct configurations for integrating anaerobic bioreactors with membrane models: Membrane modules in a side-stream AnMBR are immersed in fluid that flows past the bioreactor tank, as opposed to the internal submerged AnMBR, where the membrane is submerged in the tank itself [94]. Recent studies show that the external submerged arrangement, now only used in pilot-scale applications, has a lot of potential for use in the large-scale treatment of domestic wastewater. To summarise, Shin and Bae [95] found that pilot size external submerged AnMBR systems, which typically used hollow fibre membranes, required less energy than lab scale AnMBR and aerobic MBRs. (from 0.043 to 135.8 kWh/m^3) of an anaerobic fluidized-bed membrane bioreactor (AFMBR).

6.2. Anaerobic fluidized membrane bioreactor (AFMBR)

Although AnMBRs have demonstrated promising results for the elimination of antibiotics and other advantages, membrane fouling has prevented their widespread deployment so far. Improved antibiotic removal from wastewater and reduced cake layer formation rates are two of the goals of the recently created AFMB. It combines liquid circulation, particle sprinkling, and membrane technology. More research is required to fully comprehend how well such a revolutionary method works. Studies have shown that the AFMBR uses significantly less energy than the typical AnMBR; Compared to the standard AnMBR's range of 0.25 to 7.3 kWh m^3, its energy consumption was between 0.039 and 0.13 kWh m^3.

6.3 Membrane photobioreactor (MPBR)

The term "MPBR" refers to a membrane that is a combination of a PBR and another type of submerged micro or ultrafiltration membrane, such as hollow fibres or flat sheets. Successful microalgae separation, system stability, and higher effluent quality are just a few of the benefits of MPBR. Another major challenge is that this layout can't handle main raw household wastewater with a lot of organic matter.

This is because it often contains small amounts of organic chemicals, which can feed microalgae and stimulate their growth in order to treat wastewater [97]. The approach, in accordance with the same researchers, might effectively generate microalgal biomass while eliminating organics and nutrients at the same time, all without the requirement for an external aeration source [97].

6.4 Membrane bioreactor connected to a microbial fuel cell (MFC-MBR)

Fouling is a significant issue that inhibits MBR from being utilised more generally. Fouling phenomena and foulant deposit on the membrane surface are reduced by using an electric field in MBRs [98]. Thus, an innovative design that integrates MFCs with MBRs has recently garnered the attention of scientists. Electricity produced by MFC's wastewater treatment system can be used in the MBR to lessen its susceptibility for clogging [98]. This novel setup, as opposed to using direct electricity in MBR, lowers the amount of energy required for the procedure while preserving bacterial function unaffected by strong electric fields [99]. The findings demonstrated that the MFC-free MBR had lower SMPs' energy of adhesion to clean membranes or SPM-fouled membranes than control systems (C-MBR). Higher energy barriers on the membrane surface of the MFC-SMPS MBRs were also demonstrated, inhibiting adsorption and postponing the fouling process. The sludge flocs in MFC-MBR are less hydrophobic and have a negative surface charge as a result of the design [99].The recommended arrangement's viability in an industrial setting has been studied at several levels of detail. The amount of COD removed, the membrane's propensity for fouling, the output of biogas, and finally the highest power and current density produced utilising novel combinations were all used to assess how effective they were.

7. Fouling mitigation

The MBR is restricted in terms of the settings within which it can function. Exposing cells to starving conditions on a regular basis via a lengthy SRT increases filtering efficiency while lowering EPS and SMP production [102]. When the SRT is very lengthy, extreme fouling results from either a large MLSS buildup or an accumulation of ancient sludge (filamentous). Similar to this, low biomass will cause the MBR to operate poorly if the SRT is too short [103]. When the flow gradually decreases (the filterability deteriorates) and the TMP unexpectedly rises, it is vital to clean the membranes and maintain operational management. It is possible to clean a membrane in three distinct ways: chemically, physically, or by a combination of the two. Backwashing, a physical cleaning process in which the effluent is pumped in the reverse direction, is only useful for HF membranes. When it comes to on-site physical cleaning options, brushing is another viable option for FS membranes. Chemical cleaning can be minimised and membrane life can be prolonged by alternating between a relax/permeate phase and a backflush/permeate phase [104]. Physical cleaning can get rid of cake or coarse particles stuck to the membrane's surface, but chemical cleaning is needed to get rid of flocs. In addition to removing fouling, chemical cleaning, according to Blocher et al [105], also cleans membranes. When the fouling is not too severe, industries will often use in-situ cleaning; otherwise, ex-situ cleaning will be carried out. Most studies [39] have found that sodium hypochlorite (NaOCl) was the first chemical employed. Backwashing, a physical cleaning process in which effluent is dumped in the opposite direction, only benefits HF membranes. Brushing is yet another option for on-site physical cleaning of FS membranes. To prolong membrane life and decrease chemical cleaning cycles, Broeck et al. [104] developed a relax/filtrate cycle at the municipal wastewater influent. The answers to Eq. (above) give us the influent flow rate (Qin), the membrane area (Amem), the filtering time (tfil), and the relaxation time (trelax) (7). (trel). According to Hai et al., in situ membrane brushing was used to restart the cleaning process when the flow per unit pressure decreased. This was done because the air bubbles from the diffuser weren't effective enough to clear the membrane of all fungus. The tendency of the air bubble diffuser to direct fungus toward the membrane was the worst feature. Ex-situ cleaning and sludge removal were performed at near-zero flow rates and pressures. According to Katayon et al., the membrane configuration was laid out horizontally at the reactor's base. The fouling [33] analogy refers to the horizontal plane. Backwashing occurred at a rate of 15 seconds for every 10 minutes of permeate production, as determined by Yigit et al. After the TMP dropped to 60 kPa, sodium hypochlorite caused the first chemical backpulse. When permanent fouling developed, however, sodium hypochlorite and hydrochloric acid were used for cleaning the system outside of place [105]. The structure of the membrane plays an important role in avoiding fouling as well. Katayon et al. [33] discovered that a horizontal membrane configuration displayed slow permeate with decreasing flow compared to a vertical membrane structure. With a maximum allowable pressure fluctuation of 0.6 bar/week (0.06 kPa/week) [106], chemical cleaning is normally performed every 7-14 days. Each cleaning reduces the membrane's lifespan until a new membrane must be placed after the old one has worn out.

Since it can adsorb organic and other impurities, activated charcoal (AC) is used in the MBR as a biofouling reduction to increase BFR. Adsorption is sped up by AC with tiny diameters and few pores because of the larger surface area available. Powdered AC has a higher adsorption capacity than granular AC [107], and its larger surface area makes it more efficient at removing organic molecules with low molecular weight. Bacteria can also cling and grow on activated carbon powder (PAC).The resulting uptick in biological activity from keeping the PAC in a reactor is obvious. To improve the MBR's performance when dealing with shock loading of a hazardous chemical, Widjaja et al. [4] implemented a 10-minute set-back flushing technique. Because of its ability to adsorb organic molecules, PAC is added to biological degradation in order to improve results over non-PAC. Furthermore, once performance has stabilised, PAC's capacity can be increased to decrease COD in shock loading [4]. According to studies by Yuniarto et al.[107], the addition of PAC can boost MBR's efficacy by up to 3.8% when it comes to getting rid of high-intensity palm oil effluent. When it comes to treating palm oil mill effluent, Damayanti et al. demonstrated that three distinct types of BFRs are effective at eliminating SMP (POME). Just after PAC, Mo and Ze gave a great performance. Compare this to the surface areas of Ze (600-800 m^2/g) and Mo (713-744 m^2/g), and it's clear that the cationic polymer PAC is superior. By adding organic and inorganic components to the neutralisation mechanism and widening the floc to improve porosity in the cake layer, the PAC was able to generate flocs and boost the flux threefold above no-BFR [15][108]. When SMP is more likely to be captured in biofloc, adsorbents and coagulants can also help reduce it [109]. Membrane fouling reducer (MFR), as reported by Lee et al. flocculated activated sludge to reduce cake build up on membranes. The results demonstrated that only a little amount of MFR was required to remove significant quantities of pollutants from wastewater at 30 kPa of TPM. The neutralised sludge floc then attracted one another to produce gigantic flocs through the use of a charged neutralisation mechanism, or flocculation process. The surface assumed a positive charge when MFR concentrations exceeded the ideal level, and deflocculation began via an electrostatic repulsion mechanism [110].

8. Challenges and perspectives

One of the most advanced and creative technologies is MBR [111]. Investigations into full-scale MBRs have demonstrated that these processes are effective at treating typical pollutants while also being able to get rid of new contaminants and pathogens. For MBR operation during the winter months, extreme membrane fouling is necessary, and the specific filtration flux may rise. The initial and continuous costs of MBR would be more because tertiary care is not covered by CAS (per unit volume of treated wastewater). In comparison to CAS, MBR uses more energy but has less of an impact on the environment. Based on this analysis, it is likely that the following problems will arise with the implementation of MBR at scale: Ideal hydrodynamic conditions of the membrane module, cassette, and tank combinations are required for optimal fouling management. Membrane fouling is a complex issue that requires a more robust aeration and chemical cleaning system. The seasonal variation in fouling propensity should be taken into account when assessing the conditioning of mixed liquor for fouling management in order to maintain the rising flux over the course of long-term operations. Finally, blending membranes may increase the viability of MBR systems and make them applicable at the industrial level by resolving the issues that need further study in the experimental phase to confirm their superiority in the MBR application. However, MBRs' capital and operating expenses can be lowered, therefore this is not an insurmountable obstacle. Given the volatile nature of the membrane market, it is crucial to maintain activities aimed at extending the membrane's useful life in order to save money on depreciation. It is also necessary to lower energy consumption and increase specific flux during operating procedures in order to fulfil operational costs. This could be accomplished using post-treatment strategies and hybrid or integrated. AnMBRs (e.g., anammox, and FO). It is crucial to carefully examine all costs and needs. MBR has been used successfully with many different types of wastewater, but its competitiveness and potential application areas should still be considered. The MBR has numerous advantages, including efficient pollutant removal, stable effluent quality, minimal environmental effect, retrofit compatibility with existing infrastructure, and adaptability when paired with other processes. Technologically speaking, however, MBR is most effective when various technologies are used for a single objective, as in the treatment of industrial wastewater, or when certain attributes are strictly required, similar to how high-quality water reclamation works. These advantages may increase the technology's utility. Additionally, MBR can be used to build underground wastewater treatment plants, increasing capacity and treatment efficiency in places with limited land usage and dense populations. To maximise the AnMBR's potential for energy collection, a few hurdles must be overcome. The urgent requirement to reduce costs while utilising the AnMBR necessitates solving issues such as process inhibition, simplifying biohydrogen logistics, recovering dissolved methane, extracting and purifying the VFA, and adder.

9. CONCLUSIONS

In order to maintain MBR function, effective fouling prevention techniques and correct operation are required. This was established following numerous investigations on crucial MBR elements like design principles and the fouling problem. Each fundamental idea related to each MBR segment, including developments in control techniques, membrane modules, membrane fouling phenomena, and biological bioreactors, has been condensed in this overview. While there has been a lot of progress in the field of membrane technology, membrane fouling is still a key obstacle to its widespread use. Several difficulties and ideas have been raised as a means of suggesting further MBR research and development and potential applications.

Acknowledgments and Disclaimer

The author expresses gratitude to Dr. Vishwanath Karad of MIT World Peace University for providing them with good resources and to their teammates for their insightful contributions.

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