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Navigating the Membrane Bioreactors Operational Parameters in Eliminating Emerging Contaminants from Wastewater: A Review

Hussein M. El-Ghorab [a]*, Mahmoud M. Abdel Azeem [a], Mohamed I. Badawy [b], Tarek A. Gad Allah [b], Mahmoud S. Abdel Wahed [b], Mahmoud M. Abdelmomen [a]

[a] Public Works Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt

[b] Water Pollution Research Department, National Research Centre, Giza, Egypt

Abstract

This work delves into the critical issue of emerging contaminants in wastewater and the imperative need for their removal to safeguard water resources and human health. Various classes of emerging contaminants are identified, including pesticides, pharmaceuticals, endocrine disrupting compounds, dyes, and personal care products, each posing unique challenges. The detrimental effects of emerging contaminants on aquatic ecosystems and human health are explored, emphasizing the urgency of effective removal strategies. Methods such as advanced oxidation processes, membrane separation, adsorption, and photocatalytic processes are discussed for emerging contaminants removal, with a specific focus on the efficacy of membrane bioreactors. Different membrane Bioreactors configurations are detailed, highlighting their potential in addressing emerging contaminants. The article also covers the critical concept of some operational parameters involving the solids retention time and hydraulic retention time in membrane bioreactors, as well as other operational parameters such as flux, flux recovery, transmembrane pressure, membrane aeration rate, crossflow velocity, and cleaning cycle, and their impacts on the system performance. The importance of membrane bioreactors in treating different types of wastewater, the challenges associated with the removal of contaminants, and the mechanisms, performance evaluations, and optimization strategies for membrane bioreactors in sustainable wastewater management are also discussed.

Keyword: Emerging contaminants, hydraulic retention time, membrane bioreactor

1. Introduction

In recent times, there is a growing use of certain products whose impact on the environment is not well-documented. These products are categorized as Emerging Contaminants (ECs). Such substances have various adverse health effects on both aquatic life and humans. ECs could be of human origin or natural. Examples of such substances include pharmaceuticals and personal care products (PPCPs), Endocrine Disrupting Compounds (EDCs), flame retardants, plasticizers, perfluorinated compounds, nanoparticles, hormones, surfactants, pesticides, polycyclic aromatic hydrocarbons, and more. Table.1 shows some examples for EC substances [1].

The diagram below in Figure.1 illustrates the pathways of ECs to aquatic life and human beings through potable water, where various contaminants enter and move through the environment, from sources like households, hospitals, agricultural lands, and industries. These contaminants travel through sewage systems, surface run-off, wastewater discharge, and more, ultimately affecting water systems like rivers and oceans.

The aquatic environment is experiencing considerable repercussions due to the ecological impacts of various ECs infiltrating these ecosystems. Investigations of numerous water bodies have confirmed the presence of multiple ECs within the aquatic environment [2]. Research has demonstrated the potential threats these pollutants pose to aquatic organisms, highlighting their ecotoxicological relevance and interactions with other substances. Consequently, it is imperative to consider strategies to prevent their entry into aquatic ecosystems [3].

Advanced treatment technologies, including adsorption, advanced oxidation, membrane filtration, and membrane bioreactors, demonstrate significant efficacy in the removal of ECs and in safeguarding aquatic ecosystems [4]. This research focuses on the membrane bioreactors capabilities and performance in ECs removal.

While similar research focuses on the other aspects of this system [5], this article aims to highlight the operational parameters of the membrane bioreactors, to optimize this system in ECs removal.

*Corresponding author e-mail: husseinelghourab@eng.asu.edu.eg.; (H. M. El-Ghorab).
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Table 1 : Examples of ECs [1], [6]

Class	Examples
Pesticides	Hinosan, Alachlor, Metolachlor, Chlorpyrifos, Fipronil, Endosulfan, Atrazine, Ametryn, Malathion, Chlorophenol, Diuron, Aldrin, Endrin, Dieldrin, p,p'-DDT, p,p'-DDD, p,p'-DDE, Lindane, Hydroxybiphenyl, Isoproturon
Pharmaceuticals and personal care products (PPCPs)	Paracetamol, Ranitidinen, Salicylic acid, Sulfamethoxazole, Lincomycin, Carbamazepine, Ketoprofen, Antipyrine, Flurbiprofen, Diclofenac, Naproxen, Ibuprofen, Codeine, Azithromycin, Atenolol, Propranolol, Metoprolol, Sotalol, Flumequine, Caffeine, Diazepam, Salbutamol, Metronidazole, Trimethoprim, Ketorolac, Primidone, Alkyl-hydroxybenzoate, Triclosan
EDCs	Bisphenol-A, Propyl paraben, Ethyl paraben, Methyl paraben, Butyl paraben, Equillin, Progesterone, Oxybenzone, Octocrylene, Galaxolide, Estrone, Estriol, α-ethinyl estradiol, β-estradiol, Norgestral, Benzophenones, Phthalates
Dyes	Brilliant Green, Methylene Blue, Malachite Green, Rhodamine-B

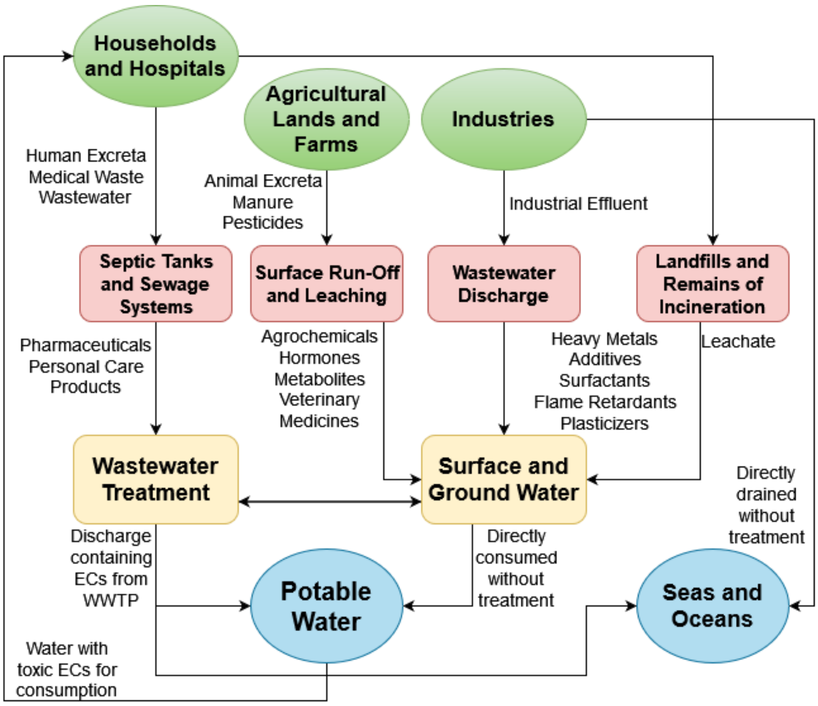

Figure 1 : Pathways of ECs [1]

2. Different types of ECs

2.1. Perfluorinated compounds (PFCs)

PFCs are man-made organic substances created by replacing all hydrogen atoms in hydrocarbons with fluorine atoms. As a result, these compounds contain C–C bonds, C–F bonds, and other functional groups. They are utilized in the manufacturing of fire-fighting foams, lubricants, varnishes, and detergents due to their unique properties such as water and oil resistance and strong molecular bonds [7]. Being highly stable to heat, light, and chemicals, they pose a serious threat as they are very persistent and can accumulate in the environment and living organisms. Significant PFCs like perfluorooctane sulfonate (PFOS) and perfluorooctane acid (PFOA) are particularly concerning because their breakdown process in the environment and living organisms is not well understood [8].

2.2. Pharmaceutical active compounds (PHACs)

PhACs, also known as human and veterinary medicines, are substances used for treating diseases. They come in different pharmacological forms, serving various purposes like reducing fever, fighting infections, relieving pain, and preventing pregnancy [9]. Livestock are given pharmaceuticals for reasons such as increasing meat and dairy production and boosting their resistance to diseases. As a result, minute amounts of these substances can be found in animal excreta. Sometimes, these animal wastes are used as fertilizers in fields, leading to the introduction of PhACs into the food chain [10].

PhACs enter the environment through multiple pathways. Human excreta contain incompletely metabolized medicines, which end up in sewage. Even after treatment, some PhACs persist and are discharged into water bodies. Additionally, improper disposal of pharmaceutical waste contributes to their presence in landfills, where wildlife may ingest them [10], [11].

Many studies have identified certain PhACs as ECs and have highlighted the associated risks, especially as endocrine disruptors, emphasizing on the importance of research addressing the removal of PhACs and personal-care products (PCPs) through different treatment methods such as bio-sorption studies on various antibiotics where various low-cost bio-sorbents suitable for remediating antibiotics from different effluents have been discussed [11]. Other studies have confirmed that PPCPs are indeed ECs due to their negative physiological effects on various environmental compartments, even at low concentrations, showing the fate of these compounds in the aquatic environment along with evaluation of their risks such as persistence, bioaccumulation, and toxicity [9].

2.3. Flame retardants (FRs)

FRs are utilized to inhibit the initiation or escalation of fire and are found in diverse transportation and consumer goods, as well as electronic and electrical equipment. They are incorporated into products during production or administered onto them and can lead to various harmful health impacts like endocrine disruption, neurological toxicity, and cancer. It has been noticed that children are particularly susceptible to the adverse effects of these substances [12], [13].

2.4. Plasticizers

Plasticizers are added to substances to increase their flexibility or pliability. They are used in materials such as plastics, dental sealants, packaging, and eyeglass lenses to make them more flexible. These additives have a low molecular weight and are primarily used in the production of plastics. Bisphenol A (BPA) and its derivative Bisphenol A diglycidyl ether (BADGE), as well as Phthalates, are recognized as potent endocrine disruptors. BPA can be found in adhesives, varnishes, paints, and food/drink containers, while phthalates are present in soaps, detergents, and pesticides [14].

2.5. Pesticides

Pesticides are chemicals used to eliminate pests and are classified based on the type of target pests, such as insecticides, herbicides, and fungicides, as well as their chemical structure, physical state, and origin. While initially used in agriculture to protect crops, they are now also used in home gardens. When an excess of these chemicals runs off into water bodies, it can pollute the water, making it unsuitable for aquatic life to thrive [15]. Additionally, the consumption of these chemicals by aquatic organisms can lead to diseases such as cancers and tumours in fish and other higher organisms in the food chain. Humans consume food grains treated with pesticides, which can cause various health hazards including birth defects, immune deficiencies, and respiratory diseases [16].

2.6. EDCs

The endocrine system comprises glands and organs that release, store, and transport hormones. EDCs are substances that disrupt the normal functioning of the endocrine system by imitating or obstructing natural hormone activities, primarily affecting sexual and reproductive development in organisms. These compounds are predominantly used in producing pesticides, PPCPs, plasticizers, fire retardants, and various other ECs [17], [18].

3. Effects of ECs on the Environment

The main emphasis will be on the aquatic environment as it is the most impacted. The harmful effects of ECs are numerous, with over 700 of them, including their byproducts and altered forms, expected to contaminate water sources and cause significant damage to aquatic ecosystems [19]. Aquatic organisms are highly susceptible to even slight changes in their surroundings. It is evident that the release of wastewater containing ECs results in the introduction of EDCs into water bodies. The existence of EDCs could lead to mutations in the genetic makeup of aquatic creatures, resulting in the ability to change one body part into another and causing genetic and reproductive disorders. The harmful effects of ECs also encompass changes in the immune system, fluctuations in sex ratios, modifications in behaviour, and feminization among aquatic species [20]. ECs accumulate as toxins in the organisms' bodies through a process known as bioaccumulation, which occurs via skin absorption or ingestion.

Bioaccumulation typically takes place at the lower levels of food chains (producers and primary consumers) as they are directly exposed to ECs. The toxicity reaches a point where it becomes lethal to the organism [21].

The continual decline of a species could result in their extinction, causing a disruption in the ecosystem. Any disturbance in the aquatic ecosystem has the potential to impact the climate. Pollution of water alters important factors (such as pH, dissolved oxygen, salinity, temperature) necessary for the survival, reproduction, and sustainability of aquatic organisms. This can lead to the movement or death of aquatic organisms, significantly disturbing the food chain. The excessive discharge of ECs leading to an increase in nutrient concentration in the aquatic environment is known as Eutrophication [22], [23].

Cultural eutrophication leads to the emergence of Harmful Algal Blooms (HABs), comprising toxic or non-toxic algae. Non-toxic algae, when decomposed, can lead to decreased oxygen levels (Hypoxia) or complete lack of oxygen (Anoxia), resulting in asphyxiation. Toxic algae produce harmful toxins that can affect both aquatic and higher organisms as they move up the food chain. The excessive growth of these algae obstructs sunlight from reaching underwater plants, hindering their growth and potentially causing an imbalance in the ecosystem [24].

Phthalates and BPAs, which are found in plasticizers, lead to genetic abnormalities in amphibians and crustaceans, while certain molluscs experience disruptions in sperm production. The excessive nitrate runoff from pesticides leads to rapid plant growth in water bodies, creating stressful conditions for spawning fish that rely on sandy areas [25]. PPCPs disrupt the sex ratios and nesting behaviours of fish. Improper incineration of hazardous medical waste, such as pharmaceuticals and plastics, releases toxins like dioxins and furans, which are not only carcinogenic to humans but also contribute to climate change and global warming [14].

The use of Bisphenol A in polycarbonate plastics can lead to early puberty, diabetes, and obesity. Exposure to high doses of dioxin by-products, which are obtained during the production of herbicides, PCBs, and other chlorinated organic compounds, can result in chloracne, a severe skin disease, as well as gastrointestinal problems, amenorrhea, and pancreatitis, especially in cases of industrial exposure or food contamination [26].

UV filters found in PCPs like sunscreens, shampoos, and insect-repellents can lead to coral bleaching when they enter water bodies through wastewater discharge. This bleaching occurs when the coral reefs expel the algae with which they have an endosymbiotic relationship, ultimately causing the reefs to die and destroying the marine organisms' habitat and shelter [27].

The most pertinent example would be that of insecticide DDT (Dichlorodiphenyltrichloroethane). The poorly water-soluble pesticide DDT builds up in zooplankton (small creatures found in aquatic environments, especially crustaceans and fish larvae). Large fish prey on these zooplankton, and in turn, are eaten by fish-eating birds. The concentration of DDT in the zooplankton was approximately 0.04 parts per million (ppm), but this increased dramatically to 25 ppm (a 10-million-fold increase) when it reached the bodies of the fish-eating birds. This demonstrates how toxins accumulate at higher levels in the food chain, a phenomenon known as biomagnification. Humans can be exposed to DDT by consuming large fish with a DDT concentration of 2 ppm, as well as through dairy products and meat. The symptoms of DDT poisoning can range from mild tremors and vomiting to severe seizures, depending on the concentration and duration of exposure [28].

In the human body, DDT is transformed into a compound called DDE, which has a significantly longer persistence than DDT. DDE was found in the serum of individuals, and even small amounts were detected in the breast milk of nursing mothers. PFCs lead to infertility and reduced lactation duration. When water is contaminated with nitrate from pesticides, it can cause Blue Baby Syndrome in human infants, which affects the blood's ability to carry oxygen. Excessive levels of fluorides in drinking water can result in dental and skeletal fluorosis, fluoride poisoning, thyroid disorders, reproductive issues, and neurological disorders [28].

The presence and harmful effects of ECs might have the potential to modify the metabolic processes of organisms. Biomagnification refers to the accumulation of toxic substances at higher trophic levels in an ecosystem. Also called bio-amplification, these toxins are transferred to higher-level organisms that consume lower-level organisms containing these toxins. Therefore, biomagnification is the result of long-term bioaccumulation [29].

ECs and their byproducts can be found in water bodies due to the limited effectiveness of traditional wastewater treatment methods in detecting and eliminating them, posing potential risks to human health. The origins and routes of ECs have been identified in various research, encompassing a wide range of known and emerging ECs with potential toxic effects [30]. Additionally, alternative approaches to addressing ECs have been explored considering the existing obstacles and limitations [31].

4. Technologies of ECs removal

The need for unconventional testing and the inefficiency of even advanced techniques in the removal of target contaminants have been considerably addressed through the development of innovative methodologies and the integration of cutting-edge technologies. These advancements have led to more effective detection and mitigation strategies, significantly improving the overall efficiency and reliability of contaminant removal processes [4].

To date, various advanced treatment systems have been investigated in the removal of ECs from wastewater. Advanced oxidation processes (AOPs) have been considered for their potent oxidizing doses, substantial presence of free radical compounds, and proven capability to cleanse wastewater streams containing organic ECs [32], [33], [34].

For instance, photocatalytic processes have been studied in the removal of organic dyes, pesticides, and pharmaceuticals [35], [36], [37], [38]. In addition, adsorption has been explored in the removal of ECs and showed promising results, where different mechanisms are presented, such as electrostatic attraction, pore filling, and biosorption [39], [40], [41], [42].

These systems may all provide the needed and sought solutions regarding the ECs removal efficiency, but they all come with a drawback or more when it comes to operation. For example, non-conventional adsorbents in adsorption-oriented processes like cyclodextrin polymers and metal-organic frameworks can be expensive to produce, and some adsorbents may have limited reusability, leading to higher operational costs. AOPs can generate harmful by-products that may require additional treatment, and techniques like ozonation require significant energy inputs, which can be costly [4].

In the last decades, membrane separation has been studied, and nanofiltration (NF) and reverse osmosis (RO) were identified as promising technologies for achieving high ECs removal where the main mechanisms responsible for removal are size exclusion, electrostatic repulsion, hydrophobic adsorption, and partitioning [43], [44].

Later on, membrane bioreactors (MBRs), which integrate an activated sludge process with membrane separation, offered an attractive solution for ECs removal, and an added efficiency of discharging less untreated micropollutants or potentially harmful by-products compared to the other methods used in EC removal such as AOP [45], [46].

Therefore, our work focuses on the MBRs capabilities in ECs removal, for their distinct advantages in providing a smaller footprint, enhanced removal mechanisms, consistent performance, and high-quality effluent, as per the previous studies that showed both effectiveness and superior performance of MBR when their operational parameters are properly addressed and adjusted [4].

5. Removal of ECs using MBRs

MBR has become widely utilized for treating municipal and industrial wastewater in recent years. Studies suggest that using an MBR is feasible for eliminating ECs, such as removing anionic ECs from drinking water [47].. There have been positive findings regarding the effectiveness of pressure-driven MBRs, gas transfer MBRs, and ion exchange MBRs for EC removal. Moreover, research has shown that MBRs exhibit promising potential for BPA removal compared to conventional activated sludge reactors (CASR), allowing for higher volume loading without compromising BPA removal efficiency [48], [49].

Furthermore, MBR proved to be more beneficial than traditional systems in PhACs and EDCs removal. The MBR effectively captured particulate matter, leading to an effluent free of suspended solids. In the case of highly adsorbing materials, total emissions were marginally lower in MBRs compared to conventional technology. MBRs showed superior solids retention time in compact reactor volumes, leading to enhanced degradation and intensified processes [50], [51].

5.1. Different MBR configurations

There are different configurations for the MBR system, with different applications for each type, and the choice of the adequate system must be considered as per the criteria of operation. First classification is based on the type of biological treatment included in the system, which can be aerobic or anaerobic.

5.1.1. Aerobic MBR

Aerobic MBRs are typically referred to as MBRs given that the aerobic biological treatment is more commonly used in this technology. In this system, microorganisms in the aerated activated sludge metabolize organic contaminants and ammonia in the presence of oxygen. Microorganisms play a crucial role in the removal of carbon by metabolizing it in the presence of dissolved oxygen, which is essential for their growth and respiration, resulting in the conversion of organic carbon into carbon dioxide. The process of ammonia removal occurs via ammonia oxidation, commonly referred to as nitrification. This nitrification process is facilitated by microbial activity and takes place in aquatic environments characterized by moderate to high levels of ammonia, sufficient dissolved oxygen, and low levels of organic carbon [52].

Given that the MBR is a coupling between both activated sludge process and membrane retention process, different setups can be found regarding the configuration of both processes in the setup.

5.1.1.1. Submerged MBR (SMBR)

For SMBRs, the submerged configuration of the membrane where the membrane sheets are immersed directly in the mixed liquor, there is a reduced risk of fouling as shown in Figure. 2. Along with its ability to prevent the accumulation of a thick cake layer on the membrane surface, with the direct exposure of aeration, also SMBRs operation with shorter sludge retention times, minimizing the chances of sludge accumulation on the membrane, resulting in better fouling resistance [53].

The removal mechanisms in SMBR can be present in adsorption onto biomass, where the microorganisms in the activated sludge biomass adsorb ECs onto their surfaces, and such interaction contributes to EC removal within the bioreactor [54]. Also, through biotransformation, the microbes metabolize ECs, breaking them down into simpler compounds. Rejection, which is due the size exclusion by the membrane poring structure, selectively retains particles based on their size. And for volatile ECs, some compounds volatilize from the mixed liquor [55], [56].

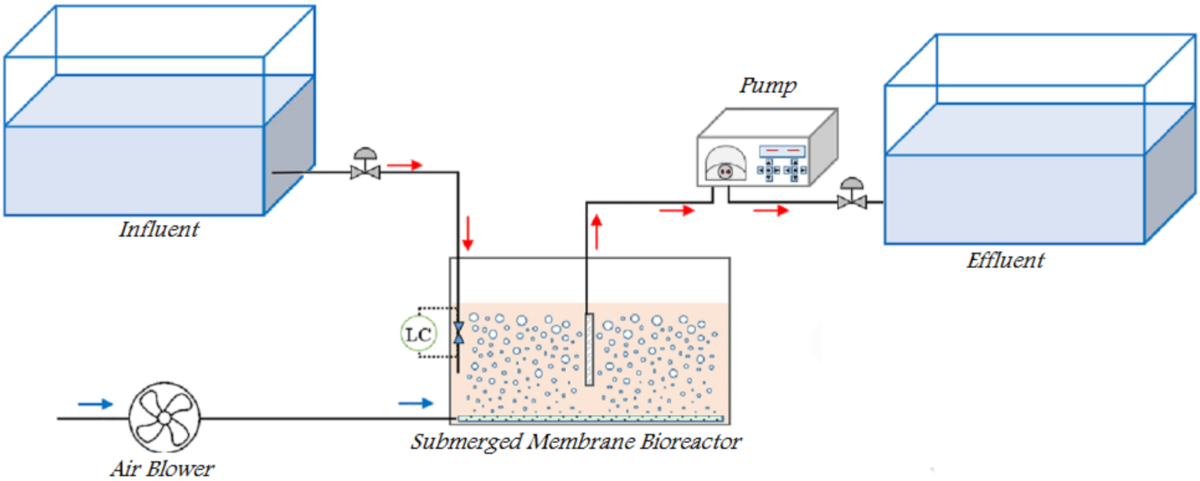

Figure 2 Schematic Drawing for SMBR Setup

5.1.1.2. Side-stream MBR (SSMBR)

In SSMBR technology, the filtration modules are positioned externally to the aerobic tank as shown in Figure. 3, which is the basis for the term “side-stream configuration”. Like immersed or submerged configurations, an aeration system is employed to both purify and provide oxygen to the microorganisms responsible for the degradation of organic materials. The biomass can be either directly pumped through multiple membrane modules arranged in series and returned to the bioreactor, or it can be directed to a collection of modules, where a secondary pump circulates the biomass through the modules in a series configuration [57]. Membrane cleaning and soaking can be performed in situ, utilizing an integrated cleaning tank, pump, and associated piping. The resultant product quality is sufficiently high to allow for its reuse in various process applications, attributable to the effective filtration capabilities of the micro- and ultrafiltration membranes [58].

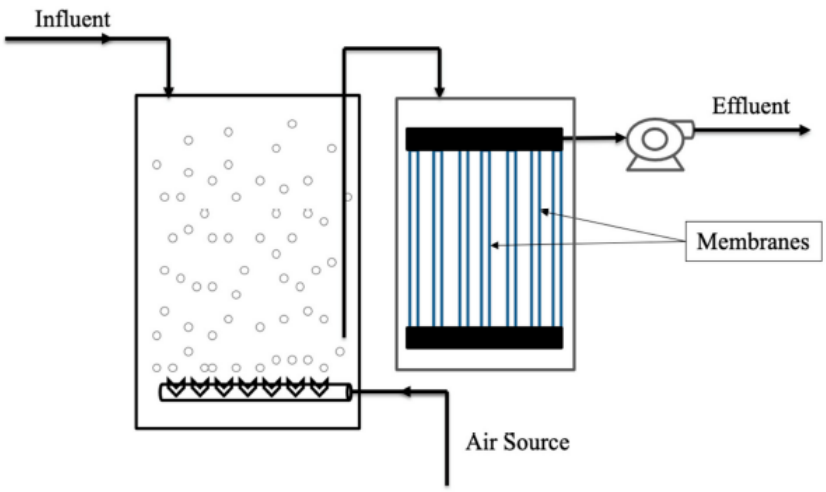

Figure 3 Schematic Drawing for SSMBR Setup

The external or side stream configuration is typically employed in applications that are smaller in scale. A significant benefit of this configuration is the ability to independently design and size both the tank and the membrane, which offers practical advantages for the operation and maintenance of the system [6]. Like other membrane processes, it is essential to create shear over the membrane surface to mitigate or prevent fouling. The external/side stream configuration achieves this shear through a pumping mechanism, whereas the internal or submerged configuration relies on aeration within the bioreactor to generate shear [59].

5.1.2. Anaerobic MBR (AnMBR)

AnMBR represents a cutting-edge approach to wastewater treatment, combining anaerobic biological processes with membrane filtration technology. This system performs multiple roles, including the thickening of sludge, interception of sludge, and removal of pollutants [60]. By utilizing membrane technology to retain pollutants, AnMBR successfully preserves both the concentration and activity of sludge within the anaerobic bioreactor. This mechanism prolongs the retention time of organic pollutants, thereby enhancing the efficiency of their degradation [61].

As shown in Figure. 4, the AnMBRs can also be configured same as the MBRs to submerged configuration or side stream, depending on the placement of the membrane sheets inside or outside the enclosed vessel in which the biological process takes place.

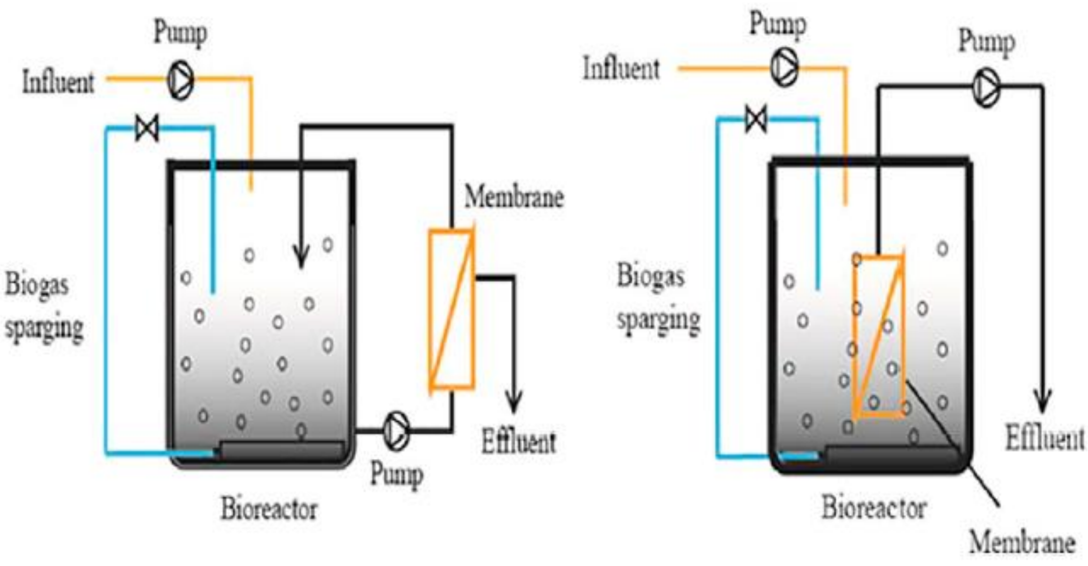

Figure 4: Schematic Drawing for Different Configurations on AnMBR

Although AnMBR exhibits notable effectiveness in treatment and produces high-quality effluent, the challenge of membrane fouling frequently leads to a considerable decline in membrane flux, which undermines system stability and hinders its broader implementation [62], [63].

Several methods are taken into consideration for mitigating membrane fouling in AnMBR such as the addition of flocculants, continuous stirring inside the reactor, vibration to membrane and mechanical scouring [64].

5.2. Membranes used in MBR

The choice of membrane material and configuration significantly impacts the performance and efficiency of MBR systems, as per their effects on the treatment process regarding adsorption and size exclusion, and performance traits such as durability and fouling [53].

5.2.1. Membrane materials

Used materials in membrane strongly affects the removal efficiency and fouling properties of the MBR, as per the properties influenced by the membrane materials such as surface charge, pore sizing, surface roughness and hydrophilicity. Careful study of the used membrane materials as per the required application can positively impact the effectiveness of the whole process [59].

5.2.1.1. Polymeric membranes

Polymeric membranes are commonly used due to their flexibility, cost-effectiveness, and ease of fabrication. Examples include polyvinylidene fluoride (PVDF), polyethersulfone (PES), and polyethylene (PE). However, they are more prone to fouling, which can reduce permeability and increase maintenance costs. While cost-effective, they can degrade under harsh chemical conditions, high temperatures or break at high presures, limiting their use in certain industrial applications [60].

5.2.1.2. Ceramic membranes

Ceramic membranes are known for their high chemical and thermal stability, mechanical strength, and long lifespan. Materials include alumina (Al_2O_3), zirconia (ZrO_2), and silicon carbide (SiC). They offer higher resistance to fouling due to their smoother surfaces and higher chemical stability, but it comes with a price of high initial cost, and the brittleness of the membrane requires careful handling [61].

5.2.2. Membrane configurations

The choice of membrane configuration in MBR systems depends on the specific requirements of the wastewater treatment application. Different configurations offer variable distinctions when it comes to cost-effective, space-constrains, maintenance, performance consistency, durability and fouling resistance.

5.2.2.1. Hollow fiber (HF) membranes

HF membranes consist of bundles of hollow fibers, providing a high surface area-to-volume ratio. They offer a large surface area for filtration, enhancing treatment capacity, and a compact design suitable for installations with space constraints due to their compact nature. They are generally more cost-effective in terms of material and installation, but are more prone to fouling, especially at high flux rates, which can reduce permeability and increase maintenance needs [65].

5.2.2.2. Flat sheet (FS) membranes

FS membranes comprise of flat membrane sheets, and they are often used in submerged MBR systems. They are easier to clean and maintain, reducing downtime and operational costs and offer higher mechanical strength compared to hollow fiber membranes, reducing the risk of damage. However, they offer a lower surface area-to-volume ratio compared to hollow fiber membranes, potentially requiring more space for the same treatment capacity, and are generally more expensive than hollow fiber membranes [66].

5.2.2.3. Tubular membranes

Tubular membranes are ideal for high-viscosity wastewater and applications requiring high mechanical strength, with their high durability and resistance to mechanical damage, making them suitable for harsh operating conditions. They have lower fouling rates due to the ability to handle higher crossflow velocities, which helps in scouring the membrane surface. Their disadvantages lie in higher energy consumption where they require higher energy inputs for operation due to the need for higher crossflow velocities, leading to higher initial and operational costs compared to hollow fiber and flat sheet membranes [67].

5.3. Main MBR operational parameters

The careful study of the operational parameters in MBR systems is critical for attaining high treatment efficiency, minimizing operational costs, and ensuring the long-term sustainability of the system, where carefully understanding and adjusting these parameters can significantly enhance the performance and reliability of MBRs in ECs removal [68].

5.3.1. Flux

Flux is the rate at which water passes through the membrane surface. The unit of permeate flux is L. m^{-2} .h^{-1}, it is indicated by J and is given by the following equation in Equation 1:[69]

$$J=\frac{\text{Permeate Flow Rate}}{\text{Area of Membrane}} \quad (1)$$

The permeate flux is associated with the trans-membrane pressure, which can be characterized as the driving force that facilitates the movement of water across the membrane. Flux can also be considered to affect the filtration effectiveness and fouling prevention. In other terms, flux changes can be attributed to fouling activity of the membrane, given that fouling contributes to blockage of membrane pores [59].

To properly study the effect of flux on MBR performance, membrane flux must be recorded, decline over time and recovery, along with other operational parameters of the membrane, to determine the behaviour of membrane fouling, and the ability of the membrane to recover its permeability either by backwash, transmembrane pressure adjustments, or other means. Generally, MBR operates at fluxes between 10 to 150 L. m^{-2} .h^{-1}, which varies based on membrane type, feedwater quality, and system configuration. The layout and the design of the MBR system plays a critical role in determining the proper flux rates, along with its effect on other parameters such as rejection and hydraulic retention time [70], [71].

5.3.2. Flux recovery

Membrane flux recovery is defined as the procedure aimed at reinstating the permeate flux of a membrane that has diminished because of fouling. This fouling occurs when particles, microorganisms, or various substances build up on the membrane's surface or infiltrate its pores, consequently resulting in a reduction of the membrane's permeability [53]. Ensuring a high rate of flux recovery is essential for the economic viability and operational effectiveness of membrane systems. This procedure contributes to extending the lifespan of the membranes and minimizing operational expenses [72].

Flux recovery as a value is the percentage of the original membrane flux that is restored after cleaning procedures are applied. Flux recovery is typically expressed by equation (2):

$$\text{Flux Recovery \%} = \frac{\text{Initial flux}}{\text{Flux after cleaning}} x100 \quad (2)$$

Flux Recovery is affected by many factors, such as the type of fouling (Organic, inorganic, and biological), membrane material where different materials react in different ways to cleaning agents and methods, and cleaning protocol where the duration, concentration of cleaning agents, and temperature can impact the success of flux recovery [53].

In MBR systems, flux recovery values were found to reach up to 32% with hydraulic cleaning methods such as backwashing. With mechanical cleaning (cleaning inside or outside the system), flux recovery can reach values of 89%. In submerged MBR systems, increasing aeration intensity can improve flux recovery by 56% [59]. There is also research dedicated to fouling mitigation in membranes for MBR systems, where flux recovery rates reach a full 100%. These values may fluctuate based on the conditions and cleaning protocols implemented. It is essential to adopt effective cleaning strategies to sustain high flux recovery and to guarantee the membrane's long-term functionality [73].

5.3.3. Transmembrane pressure (TMP)

TMP serves as a vital parameter that significantly affects the operational performance and efficiency of membrane systems. TMP is defined as the pressure differential between the feed side and the permeate side of the membrane. In MBRs, TMP can fluctuate based on various factors, including the membrane type, characteristics of the feed water, and the specific operational conditions in place [74].

Under typical operating circumstances, TMP values generally fall within the range of 0.1 to 0.5 bar (10 to 50 kPa or 1.45 to 7.25 psi). When membranes are in a clean and new state, TMP values tend to be lower, typically between 0.1 and 0.2 bar (10 to 20 kPa or 1.45 to 2.9 psi). However, as fouling develops, TMP values may rise. Operators often establish a maximum TMP limit (for instance, between 0.5 and 1.0 bar or 50 to 100 kPa) to initiate cleaning protocols. In instances of significant fouling or elevated solids concentration in the feed water, TMP may surpass 1.0 bar (100 kPa or 14.5 psi), which requires more frequent cleaning interventions [53], [75], [76].

It is essential to maintain TMP within an optimal range to ensure the effective operation of MBRs and to mitigate the risks of excessive fouling and potential membrane damage. Consistent monitoring and maintenance practices are critical for the effective management of TMP [77].

5.3.4. Membrane aeration rate

The aeration rate serves as a vital parameter in aerobic MBRs, exerting a significant influence on the system's overall performance, especially regarding the management of membrane fouling in SMBR systems, oxygen transfer efficiency, and total energy usage. Aeration plays a key role in cleaning the membrane surface, thereby minimizing the buildup of foulants. While elevated aeration rates can enhance fouling management, they may also lead to increased operational expenses, as aeration represents one of the primary energy-intensive operations within MBRs. Therefore, optimizing the aeration rate is essential to achieve a balance between effective fouling control and energy efficiency. Proper aeration is essential to provide adequate oxygen for microbial processes, which are critical for the biodegradation of ECs present in the influent. Inadequate aeration can result in suboptimal treatment outcomes [53], [78].

Aeration rates of approximately 0.15 m^3/h have demonstrated effectiveness in particular applications, notably in the treatment of dye wastewater, where they achieve significant removal efficiencies for chemical oxygen demand (COD), ammonium, nitrogen, and color. Typically, aeration rates ranging from 0.8 to 1.2 m^3 of air per square meter of membrane area per hour are employed to optimize the control of membrane fouling and to preserve favourable sludge properties [79], [80]. However, when aeration rates exceed 1.2 m^3 of air per square meter of membrane area per hour, there is potential for enhanced fouling control, although at the cost of increased energy consumption and possible adverse effects on biomass characteristics. Rates reaching up to 10 m^3 were found to be used where minimum fouling occurred to membrane and consistent flux rate was attained [81].

In the context of aeration optimization strategies, the Specific Aeration Demand for membrane scouring (SADm) serves as a crucial metric for assessing energy efficiency. A reduction in SADm values signifies the implementation of more effective aeration methods [69]. The adoption of intermittent aeration has the potential to lower energy usage while still ensuring proper fouling management. Additionally, employing techniques such as fine bubble aeration or diffusers can enhance oxygen transfer efficiency and decrease energy expenditures. Also measuring the dissolved oxygen (DO) in the bioreactor and maintaining it at required values for biodegradation can be a governing factor in optimizing the aeration rates. It is vital to optimize the aeration rate to strike a balance between effective control of membrane fouling, sufficient oxygen delivery, and energy efficiency within MBR systems [82], [83].

5.3.5. Crossflow velocity (CFV)

CFV serves as a critical parameter in MBRs, significantly affecting the hydrodynamic environment at the membrane interface. By generating a shear force, CFV plays a vital role in minimizing fouling and concentration polarization, thereby preventing the accumulation of particles on the membrane surface. In certain configurations, such as AnMBR and SSMBR, CFV is predominantly relied upon for controlling fouling, as aeration does not substantially contribute to fouling reduction in these systems [84], [85].

CFV as a value is the linear velocity of the flow tangential to the membrane surface. It is calculated by equation (3): [69]

$$CFV = \frac{\text{Volumetric Flow Rate}}{\text{Cross Sectional Area of Flow}} \quad (3)$$

Higher CFV contributes to the mitigation of membrane fouling by augmenting shear forces that inhibit the accumulation of particles on the membrane surface. By sustaining an optimal CFV, one can enhance membrane flux and permeability through the reduction of fouling layer development. Although increased CFV can improve fouling management, it simultaneously leads to higher energy consumption. Consequently, the optimization of CFV is essential for achieving a balance between operational performance and energy efficiency [84], [85].

Typical Values of CFV can have a lower range of around 0.1 to 0.2 m/s, when used in systems with lower fouling tendencies. Moderate CFV between 0.2 to 0.5 m/s are commonly used in many MBR applications to balance fouling control and energy use. High CFV above 0.5 m/s can be reached when used in high-fouling conditions but with higher energy costs. In SSMBR configurations, high CFVs are often used to reduce fouling. Typical CFV values can range from 1 to 3 m/s. This high velocity helps in maintaining a lower fouling tendency but requires significant energy input [86], [87]. In AnMBRs, high shear operation is achieved through high CFV, which can promote higher fluxes. CFV values in these systems can be around 0.5 to 1.5 m/s, depending on the specific application and wastewater characteristics [88].

Understanding and optimizing CFV is essential for the efficient operation of MBR systems, particularly in applications where fouling is a significant concern. Optimization strategies will always be required for adjusting flow rates to achieve the desired CFV without excessive energy consumption. Also designing flow channels to optimize CFV and enhance shear forces should be studied. An energy efficient solution could be using intermittent high CFV to periodically clean the membrane surface while maintaining lower CFV during regular operation to save energy [87].

5.3.6. Hydraulic retention time (HRT)

HRT is the average time that wastewater remains in the bioreactor. It is calculated as the ratio of the reactor volume (V) to the influent flow rate (Q) as shown in equation (4):

$$HRT=V/Q \quad (4)$$

(V) is the volume of the bioreactor (in cubic meters) and (Q) is the flow rate of the influent (in cubic meters per hour) [69].

Adequate HRT ensures sufficient contact time between the wastewater and the microorganisms, allowing for effective biodegradation of organic pollutants and ECs. Furthermore, proper HRT helps in maintaining stable microbial populations and consistent treatment performance and impacts the removal efficiency of nutrients like nitrogen and phosphorus, which require specific retention times for complete biochemical reactions [5].

Modifying the influent flow rate to achieve the desired HRT is required for optimizing treatment efficiency. Another parameter for HRT optimization is designing bioreactors with appropriate volumes and dimensions to match the expected influent flow rates and treatment requirements. Regular monitoring of HRT and adjusting operational parameters is required to maintain optimal performance [59].

HRT values in MBR systems typically range from 3 to 10 hours. For municipal wastewater, HRT values are often between 4 to 8 hours to ensure effective removal of organic matter and nutrients, where for industrial wastewater, it depends on the complexity and concentration of pollutants, and HRT can vary widely, often requiring longer retention times. Table 2 shows different research in optimum HRT based in the used configuration and target pollutants.

5.3.7. Solids retention time (SRT)

SRT is the average time that biomass (sludge) remains in the bioreactor. It is calculated as the ratio of the mass of solids in the reactor to the mass of solids removed per day as per equation (5).

$$SRT = \frac{Mass\ of\ solids\ in\ the\ reactor}{Mass\ of\ solids\ removed\ per\ day} \quad \text{also expressed as } SRT = \frac{V.X}{Qw \cdot Xw} \ (5)$$

(V) is the reactor volume, (X) is the mixed liquor suspended solids (MLSS) concentration, (Qw) is the waste sludge flow rate, and (Xw) is the concentration of solids in the waste sludge [89].

The importance of optimizing SRT can be found in many aspects. For microbial population control, SRT determines the composition and concentration of the microbial population in the bioreactor. Longer SRTs allow for the growth of slower-growing microorganisms, which are essential for processes like nitrification and denitrification [89]. Also, when it comes to sludge production study, higher SRTs generally result in lower sludge production, as more biomass is retained and degraded within the system. As for nutrient removal, effective nutrient removal, particularly nitrogen and phosphorus, often requires longer SRTs to ensure complete biochemical reactions. Furthermore, maintaining an optimal SRT helps in achieving stable and efficient system performance, reducing the risk of process upsets [90].

The impact of SRT on the performance of the MBR is contribution to membrane fouling, where longer SRTs can lead to higher concentrations of extracellular polymeric substances (EPS) and soluble microbial products (SMP), which contribute to fouling [91]. As for biomass characteristics, SRT influences the characteristics of the biomass, including particle size distribution, viscosity, and zeta potential, all of which affect membrane filtration resistance. Optimal SRT enhances the removal efficiency of organic pollutants and nutrients, leading to better effluent quality [92], [93].

Table 2: HRT and SRT Values from Various Studies

Configuration	Target Pollutant(s)	HRT (hours)	SRT (days)	Ref.
Submerged forward osmotic MBR	Carbamazepine	Ranged from 25h to 150h during an 80 day operation	30d	[97]
Single Species SMBR	Malathion [(Diethyl 2-dimethoxyphosphinothioyl) sulfanyl] butanedioate	72h based on the flask study experiments where the complete degradation of malathion was achieved by the microorganism.	No discharge condition was set for the sludge during the operation	[98]
SMBR with hollow fiber polyvinylidene fluoride (PVDF) microfiltration membrane	Acetaminophen, 17β-estradiol, Naproxen, Diclofenac sodium, and Carbamazepine	6h	-	[99]
SMBR with Al2O3-based flat-sheet ceramic membrane	Carbamazepine	Ranges from 12 to 24h were studied, optimum value was found to be 24h	Ranges from 5 to 15d were studied, optimum value was found to be 5d	[100]
SMBR with hollow fiber membrane	Hospital Wastewater containing Ibuprofen, Hydroxy-ibuprofen, Diclofenac, Hydroxy diclofenac, Acebutolol, Estrone, Sulfamethoxazole, Clarithromycin, Desvenlafaxine, Caffeine, Carbamazepine	18h	100d	[101]
SMBR with hollow fiber membrane	Di 2-ethyl hexyl phthalate (DEHP)	Ranges from 4 to 8h were studied, optimum value was found to be 4h	140d	[14]
SMBR integrating sponge-plastic biocarriers	Sulfonamide antibiotics (sulfadiazine and sulfamethoxazole)	12h	45d	[102]
MBR Coupled with Ozonation	Azithromycin, Trimethoprim, Diclofenac, Naproxen, Levonorgestrel, Medroxyprogesterone	12h	-	[103]
Two Step Anoxic – Aerobic MBR	Amoxicillin, Acetaminophen, Triclosan, Atrazine, Estrone	Ranges from 4 to 20h were studied, optimum value was found to be 12h	-	[104]
SMBR with polyacrylonitrile membrane	PCPs (Triclosan, Methylparaben, Ethylparaben, Propylparaben, Butylparaben, 2-Phenoxyethanol, Galaxolide, Musk Ketone, Ethylhexy, Methoxycinnamate)	Ranges from 8 to 24h were studied, optimum value was found to be 16h	No sludge discharged from reactor during the operating experiment	[70]
SMBR with polyethersulfone hollow fiber membrane	Acetaminophen, Ketoprofen, Naproxen, Roxithromycin, Sulfamethoxazole, Trimethoprim	9h and 13h periods were studied, 13h was more effective	15 and 30d periods were studied, 30d was more effective	[105]
Anaerobic osmotic MBR	17α-ethinylestradiol, betamethasone, fenofibrate, fluconazole, ketoprofen, loratadine and prednisone	240h	45d	[106]
SMBR with hollow fiber membrane	Diclofenac, sulfamethoxazole, trimethoprim, carbamazepine, tramadol, naproxen, propranolol, ibuprofen, triclosan, gemfibrozil	6h	Zero Sludge Waste, 15d, and 30d, 30d and zero waste was optimum	[107]

Different periods of SRT from previous studies can be seen in Table. 2. SRT period should be decided based on the type of wastewater, required operational aspects, and impact on other parameters, where the period must ensure effective organic matter and nutrient removal and can extend to longer periods to handle specific contaminants depending on the complexity of the wastewater. SRT values can be typically low around 5 to 10 days, often used in systems where rapid biomass turnover is desired. Moderate SRT values between 10 to 30 days are commonly used in municipal wastewater treatment to balance sludge production and nutrient removal. Longer SRT values exceeding 30 days are used in applications requiring extensive nutrient removal and lower sludge production [92], [94].

Optimization strategies must be studied in operation of MBR to properly tweak the required SRT value. Adjusting waste sludge flow rate can achieve the desired SRT without compromising treatment efficiency, and regular monitoring of MLSS and other biomass characteristics is needed to maintain optimal SRT. Appropriate SRT management would balance between minimizing membrane fouling and maximizing treatment efficiency [95], [96].

5.3.8. Cleaning cycle and protocols

The process of membrane cleaning plays a crucial role in mitigating and managing membrane fouling, lowering TMP, and rejuvenating membrane flux. In the context of MBR operations, the techniques employed for contaminant removal can be categorized into two main types: physical cleaning, and chemical cleaning. However, achieving optimal cleaning outcomes through a singular approach is often challenging in practical applications. Typically, an effective cleaning strategy involves the integration of multiple methods. To ensure sustained membrane performance, regular cleaning is imperative. The specific cleaning protocols may differ depending on the design of the system and the characteristics of fouling [53].

5.3.8.1. Physical cleaning

Physical cleaning primarily targets the removal of reversible contaminants from both the surface and pores of membranes. The predominant techniques employed in this process include aeration, backwashing (utilizing either air or filtrate), ultrasonication, sponge scrubbing, and water washing. This approach enables MBRs to maintain a relatively stable flux while minimizing the risk of secondary contamination; however, it necessitates frequent cleaning, which can lead to increased operational costs. Among these methods, aeration is the most utilized cleaning technique in aerobic SMBRs. It leverages the crossflow generated by rising air to mitigate particle deposition on the membrane surface and to dislodge surface pollutants, thereby alleviating membrane fouling. The combination of intermittent operation with aeration can further improve the dispersion of contaminants adhering to the membrane and effectively retard membrane fouling [108].

For physical cleaning by backwashing, backflushing is performed for 30 to 60 seconds. This can occur every 10 minutes during an operation involving reversing the flow through the membrane to dislodge and remove fouling particles [83].

Relaxation is also a physical cleaning method where the filtration is stopped temporarily while air scouring continues to help dislodge particulate matter from the membrane surface. Relaxation periods can last for a couple of minutes, often integrated into the operational cycle, occurring every 10 to 20 minutes [100], [109].

Another physical cleaning method is ultrasonic irradiation which serves as an effective method for cleaning fouled membranes by inducing significant physical action, such as microjets, micro streams, and shock waves. These procedures facilitate the detachment of particles from the fouled membrane at the heterogeneous liquid-solid interface [110]. Additionally, the generation of active hydroxyl radicals during ultrasonic irradiation plays a crucial role in targeting and degrading the adsorbed foulants, thereby aiding in the control of membrane fouling. The ultrasonic cleaning approach can also be enhanced by integrating it with other cleaning techniques, such as chemical cleaning and backwashing, to further increase cleaning efficiency [111].

5.3.8.2. Chemical cleaning

Chemical cleaning becomes necessary when physical cleaning fails to adequately address membrane fouling issues. When undertaking chemical cleaning, four critical factors must be considered: the type of the cleaning agent, its concentration, the duration of contact, and the mechanical strength of the membrane [112].

Common chemical agents employed in this process include alkaline cleaning agents, acidic cleaning agents, oxidizing agents, and surfactants such as ethylenediaminetetraacetic acid (EDTA) and ammonium hydrogen fluoride. Alkaline cleaning agents are particularly effective in eliminating organic materials and biological contaminants [113]. The cleaning procedure involves several steps: first, water is introduced into the cleaning tank and heated using steam. The cleaning pump is then activated, and the cleaning agent is gradually added, ensuring complete dissolution. The first section of the membrane is cleaned, followed by the second section, with dynamic circulation maintained for 40 minutes, followed by a 50-minute soaking period. If the pH decreases by 0.5, sodium hydroxide is added to maintain the pH within the range of 10 to 11. Once the pH stabilizes, water rinsing is performed until the effluent pH reaches 6 to 7, indicating the completion of the washing process [114].

Acidic cleaning agents are effective against mineral and inorganic fouling. The acid cleaning procedure mirrors that of alkaline cleaning, with water heated in the cleaning tank, followed by the gradual addition of hydrochloric acid while maintaining a pH of 2 to 3. Cleaning occurs in sections, with each section undergoing 40 minutes of dynamic circulation followed by 40 minutes of immersion. Once the pH ceases to rise, water rinsing is initiated, concluding when the effluent pH reaches 6 to 7. Hydrochloric acid is particularly adept at removing hydrophobic organic compounds, while sodium hydroxide is more effective against organic pollutants. The synergistic use of both agents can enhance the removal of surface contaminants on the membrane, although their efficacy in eliminating pollutants within the membrane pores is limited [115], [116].

Oxidizing cleaning agents serve to enhance the hydrophilicity of organic polymer contaminants, effectively dislodging adherent materials from the membrane's pores. A surfactant enhances the interaction between the cleaning agent and contaminants, thereby increasing the efficacy of the cleaning process. Additionally, it has the capability to disrupt bacterial cell walls and mitigate the effects of biofilm-related foulants. Chemical cleaning methods can be applied in both on-line and off-line scenarios, significantly restoring membrane flux; however, the resultant cleaning waste may occasionally lead to secondary fouling issues [117].

Chemically enhanced backwash (CEB) represents a novel approach that integrates physical backwashing with chemical cleaning techniques, demonstrating significant efficacy in restoring membrane permeability. This method is particularly effective in eliminating both organic and inorganic foulants from the membrane's surface and pores, addressing limitations often encountered with conventional physical cleaning methods. Regular implementation of CEB contributes to the stabilization of TMP and the maintenance of elevated permeate flux, thereby ensuring reliable system performance [118]. By proficiently managing fouling, CEB can extend the operational lifespan of membrane modules. Common oxidants utilized in this process include sodium hypochlorite ($NaClO$), which is particularly effective against organic contaminants. Additionally, acids and bases such as citric acid and sodium hydroxide ($NaOH$) are frequently employed to target inorganic fouling and biofilms. Typically, CEB is conducted two to three times weekly, with each cycle lasting between 30 to 60 minutes [118], [119].

6. MBR performance in ECS removal

The basics of MBR performance in ECs removal is combining a suspended growth biological reactor with solid removal and filtration. MBRs consistently produce high-quality effluent with low concentrations of bacteria, total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus. As for EC's, Table. 3 shows different research regarding the degree of removal obtained using MBR.

7. ECs main removal mechanism in MBR

MBRs leverage a combination of removal mechanisms to achieve high-quality effluent and high EC's retention. Understanding these removal mechanisms is essential in order to integrate an MBR system that would successfully provide the required outcomes based on the wastewater characteristics and operational conditions [5].

7.1. Biodegradation

Microorganisms in the MBR play a crucial role in the degradation of pollutants. They metabolize organic materials, nitrogenous substances, and various other contaminants found in wastewater. This process of biodegradation resembles that of traditional activated sludge systems, yet it is enhanced by the incorporation of membrane separation technology. And due to the organic nature of the ECs, biodegradation can play a major role in their removal. However, a lot of considerations must be dealt with to ensure maximizing the efficiency of the biodegradation share [129].

In removal of ECs using anaerobic fluidized MBR, biodegradation contributed to removal of more than 80% of benzothiazole, benzotriazole, 17α-ethinylestradiol, 17β-estradiol, Amoxicillin and Diclofenac. The microbial communities involved in biodegradation are composed of various groups, including fermentative bacteria, methanogens, and bacteria that reduce sulfate, iron, and nitrate. The diversity of degradation pathways affects the overall removal efficiencies [128], [130].

Studying the biological parameters along with the operational parameters of the MBR is crucial for a successful system, like identifying the microbial communities and the effect of the water toxicity on their populations and also deciding on the MBR setup most fit for the required biological interaction. As for the operational parameters, optimizing the HRT, flux rate, SRT, cleaning and aeration can have a great impact on the biodegradation efficiency [70], [131].

7.2. Sorption

Sorption refers to the adsorption of pollutants onto the biomass (microorganisms) or the membrane surface. As water flows through the MBR, contaminants can adhere to the microbial flocs or directly onto the membrane material. This dual sorption mechanism contributes to overall removal efficiency. If a compound has a strong affinity for binding to solid particles (like the biomass in MBRs), it tends to get adsorbed onto those particles [132].

Table 3: Removal ratios of different ECs by MBR

Target Pollutant	Removal	Notes	Ref.
Ibuprofen Diclofenac Ketoprofen Naproxen	95% 50% 95% 95%	iclofenac accumulation in activated of MBR working with high SRT and HRT lead to low removal ratio	[120]
Sulfadiazine Sulfamethoxazole	91% 88%	Aerobic SMBR integrating sponge-plastic biocarriers showed better removal ratios than conventional SMBR	[102]
Trimethoprim Sulfamethoxazole	88% 96%	Rice straw was added as biological carrier and denitrification carbon ource, nitrification co-metabolism highly contributed to two antibiotics degradation	[121]
Di 2-ethyl hexyl phthalate	98%	High SRT used demonstrated substantial effect on the removal.	[14]
Caffeine	88%	Efficiently methanogenic digestion has been achieved by the AnMBR, even at a relatively short HRT of 5d	[122]
Carbamazepine	95%	Oxidation, hydroxylation, and decarboxylation were defined as the primary carbamazepine degradation mechanism	[97]
Amoxicillin	84%	dsorption and biodegradation represented the largest removed fraction of amoxicillin	[123]
17β-estradiol Testosterone	95% 100%	Size exclusion was dominant, especially with NF and RO membranes	[124]
Caffeine Triclosan Carbamazepine	94% 90% 36%	Carbamazepine being a recalcitrant compound had a low removal ratio	[125]
Triclosan Methylparaben Ethylparaben Propylparaben Butylparaben 2-Phenoxyethanol Galaxolide, Musk Ketone thylhexy- Methoxycinnamate	98% 99% 64% 100% 75% 100% 91% 90% 99%	RT had a major effect on the removal ratio, 16h was found to be the optimum HRT period	[70]
methyl orange	100%	emethylation and desulfonation were the mechanism of methyle orange degradation in anaerobic baffled MBR	[126]
Atrazine	96%	icroorganisms isolated from activated sludge of a pilot scale MBR plant were optimized to enhance the biodegradation efficiency of atrazine	[127]
Naproxen, diclofenac, azithromycin, trimethoprim, levonorgestrel, medroxyprogesterone	100%	ombining MBR with ozonation could significantly enhance the removal of pharmaceuticals, system optimization was done using Response Surface Methodology (RSM)	[103]
benzothiazole benzotriazole	100% 97%	The removal due to biotransformation was 88% for benzothiazole and % for benzotriazole, the remaining removal percentage was attributed to be retained by the membrane.	[128]

MBRs operating with longer SRTs and higher biomass concentrations contributes to better ECs removal. The MBR membrane acts as an effective barrier. Many ECs can adsorb onto the membrane surface, forming a "cake layer." This layer can potentially prevent the escape of extracellular enzymes and soluble oxidants, creating a more active biological mixture capable of degrading a wider range of carbon sources [133].

Research into the elimination of prevalent quinolone antibiotics from wastewater was conducted using MBR, where sorption of these antibiotics onto the sludge was the primary removal mechanism, reaching up to 78% removal percentage, followed by their biodegradation in the solid mass. ECs which are not readily biodegradable will require more focus on sorption removal mechanisms [134].

7.3. Size exclusion

MBR membranes have pores of varying sizes. When wastewater passes through these membranes, larger particles (including some ECs) are physically blocked by the membrane pores. Essentially, it's like a sieve that selectively allows smaller molecules to pass through while retaining larger ones. Steric hindrance occurs when molecules are too large to fit through the membrane pores due to their shape or spatial arrangement. Even if a contaminant is small enough based on its molecular weight, steric effects can prevent its passage through the membrane [135]. Membranes can also interact with charged contaminants through electrostatic forces. Positively or negatively charged ECs may be repelled or attracted by the membrane surface, affecting their removal [136].

For Reverse Osmosis (RO) and Nanofiltration (NF), these high-pressure membrane processes exhibit excellent removal rates for ECs. For compounds like estrone and testosterone, removal rates often exceed 95%. Ultrafiltration (UF): UF membranes operate at lower pressures and primarily rely on size exclusion. They effectively remove larger ECs and suspended solids. While they may not achieve the same high removal rates as RO or NF, they still contribute significantly to overall removal [137].

8. Conclusion

There is a critical need for effective removal of ECs from wastewater to mitigate environmental and public health risks. The diverse range of ECs are present in wastewater, such as PPCPs, and pesticides, each requiring tailored removal approaches. MBRs are identified as a promising technology for EC removal, offering high-quality effluent and efficient removal rates.

The significance of optimizing the operational parameters for the MBR system is crucial given that it affects the performance of the system in ECs removal, fouling behaviour of the membrane, and the energy consumption of the system. All MBR aspects are generally impacted by each other, changes in any parameter will most probably influence other parameters, fouling of the membrane, and ultimately the membrane performance. Therefore, it is important to carefully optimize and select the adequate values for the MBR operation.

Also, understanding the wastewater quality including the ECs of which their removal is required, along with the required effluent quality, is required for choosing the optimum MBR configuration, whether the required treatment would be aerobic, anaerobic, or a mix of both systems, and proper study of the removal mechanisms of the target pollutants would substantially help in targeting the areas of the system that requires focus or enhancements.

Most importantly, behaviour of an MBR system is impacted by the type of pollutants that requires removal. Different classes of ECs exhibit different requirements from MBR for optimization. It’s essential to thoroughly study the system in hand when tackling the efficiency of MBR removal for certain pollutant, the removal mechanisms involved and their contribution, and the required operational parameters for efficient removal.

9. Conflicts of interest

There are no conflicts to declare.

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11. References

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