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Review Article

Wastewater Treatment by using Membrane Bioreactor (MBR): State of the Technology and the Industrial Challenges

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Abstract
The treatment of water and wastewater is significantly enhanced by membrane technology, particularly when combined with biological systems in Membrane Bioreactors (MBRs). These integrated systems offer enhanced functionality, including the effective removal of refractory organics and recalcitrant compounds. MBRs have emerged as a promising solution for large-scale water and wastewater treatment, offering efficient performance and a reduced footprint compared to conventional systems. However, economic constraints pose significant challenges to widespread MBR implementation. This paper comprehensively examines the practical challenges associated with MBR technology, delving into various MBR types and their applications. It conducts a detailed analysis of MBR strengths and weaknesses, supported by relevant studies and data. Additionally, the economic feasibility of MBR systems is disused, considering factors such as energy consumption, membrane fouling, and maintenance costs. Furthermore, this paper reviews the utilization of membrane systems in diverse wastewater treatment scenarios, encompassing municipal, pharmaceutical, and industrial effluents. It showcases MBR technology's efficacy in achieving stringent effluent quality standards and complying with environmental regulations through case studies. The insights presented in this paper contribute to a better understanding of MBR technology and inform future developments in the field. This study aims to promote wider adoption of MBRs as a sustainable and efficient solution for global water and wastewater treatment.
Keywords: Membrane Bioreactor, Membrane fouling, Wastewater treatment, Refractory organics, Recalcitrant compound

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Introduction

As the global population grows, so does the demand for safe drinking water. Human population and climate changes are two main factors that cause water shortage (Kadhom & Deng, 2018). Nevertheless, human population growth affects water shortage four times more than climate change (Kummu et al., 2010). Wastewater is a great source of water if it is treated correctly (Zahed et al., 2020). There are several new technologies for wastewater treatment. for instance: Electrochemical oxidation (Shao et al., 2020), Membrane Distillation (MD) (Ren et al., 2018), and Microbial Electrochemical Technologies (MET) (Das et al., 2019). Rapid industrialization and pharmaceutical progress have caused increasing refractory pollutants to be disposed of in the water. It is essential to know how these contaminations will be removed from the water. Activated charcoals or other adsorbents eliminate refractory organics, which may cause secondary problems. For instance, the disposal of the contaminated absorbents or proper treatment and containment of such hazardous waste compounds the cost of the system (Das et al., 2019). Thus, we have to look for alternative solutions to solve this problem. Besides, hospital and pharmaceutical wastewaters can make several bacterial species resistant. After resistant pathogenic species that have been reported in hospitals, pharmaceutical contaminants are known to be one of the causes of antibiotic resistance (Szczepanowski et al., 2009). Heavy metals and biocides such as zinc and triclosan promote resistant gene transfer in bacteria (Martinez, 2009).

Moreover, there is a significant risk of contamination in treated water in the dairy industry. Thus, using treated wastewater for washing equipment in direct contact with raw milk should be avoided. On the other hand, the treated wastewater can be used in cooling towers and boilers or for manufacturing practices like washing floors (Andrade et al., 2015).

Conventional wastewater treatment methods, such as the activated sludge process, trickling filters, rotating biological contactors (RBCs), and constructed wetlands, are not efficient and feasible enough due to their restriction and limiting factors. These methods face challenges such as excessive sludge formation, clogging, biofilm detachment, sensitivity to hydraulic and organic loading fluctuations, high energy requirements, and limitations in contaminant removal. These factors hinder their ability to consistently achieve high treatment efficiency, control operational costs, and meet stringent effluent quality standards (Crini & Lichtfouse, 2019), (Waqas & Bilad, 2019), (Wu et al., 2015), (Daigger & Boltz, 2011). Hence, Conventional wastewater treatment methods are inadequate in terms of their effectiveness and sustainability for meeting the requirements of wastewater recovery. Therefore, there is a pressing need to adopt more efficient and feasible methods in order to achieve sustainability objectives.

This research aims to investigate the effectiveness of membrane bioreactors in water treatment, their industrial challenges, and opportunities in detail.

Data Gathering Methodology:

To conduct this review, a comprehensive search was conducted across multiple scholarly databases, including Scopus, Web of Science, and ScienceDirect. These databases were chosen due to their extensive coverage of scientific literature across various disciplines. The search strategy involved utilizing a combination of relevant keywords and terms related to membrane bioreactors (MBRs), wastewater treatment, membrane technology, and membrane fouling. Boolean operators (AND, OR) were employed to refine the search and ensure the inclusion of relevant studies.

The search was conducted to encompass articles published up to 2023 to ensure the inclusion of the most recent research findings. In addition to the initial database search, a manual screening of reference lists from selected articles was performed to identify additional relevant studies.

The inclusion criteria for selecting studies involved focusing on research articles, reviews, and case studies that provided valuable insights into the applications, challenges, and future prospects of MBR technology in wastewater treatment. Non-English articles were excluded from the review to maintain consistency and ensure accurate interpretation of the findings.

Through this rigorous selection process, a comprehensive collection of relevant literature was obtained for the analysis and synthesis presented in this review article. The findings and insights derived from the selected studies have contributed to the understanding of the significant applications, challenges, and potential advancements in MBR technology for water and wastewater treatment.

Application of membrane

Using membranes for removing contaminants from water has been a widely studied subject due to its higher efficiency than other methods (Zuo et al., 2021). Membranes were first applied to treat water, but now they are also being used for desalination flocculation, sediment purification techniques, extraction, nitrogen recovery, drug release control, dialysis, distillation, and culture medium recycling, as they can remove protozoans, bacteria, and viruses, but maintain residual nutrients (Ahmad et al., 2021; Drexler & Yeh, 2014).

Microplastics (plastic particles less than 5mm) may have ecotoxicological impacts on flora and fauna. Thus, a wastewater treatment system should be able to obstruct the release of microplastics. Researches render that MBR could remove up to 99.9% of microplastics. This fact advocates MBR as a sustainable solution to the issue of microplastic contaminations (Kundu et al., 2021; Xiao et al., 2019; L. Zhang et al., 2021). Beyond the microplastics, the nano plastics' existence deserves to be paid more attention. Nanoplastics are mainly produced in wastewater treatment plants due to the breakdown of plastic particles (Enfrin et al., 2019). Recent studies have developed techniques based on bio-nano filtration and membrane technology that can remove nano plastics successfully (Mohana et al., 2021; Pramanik et al., 2021).

Pharmaceutical wastewaters is another concern. The contaminants of pharmaceutical industries are organic chemicals made up of complex structures and are resistant to biological degradation (Carballa et al., 2004). Complicated water quality, the abundance of refractory substances, and high salinity are the main properties of antibiotic pharmaceutical wastewater (Zhao et al., 2019). These wastes can be disposed of in feces and urine, and then they will be emitted into the sewage system (Gu et al., 2018).

One of the critical challenges of the membranes system is fouling. Creative methods like applying electric fields and nanomaterials are focused on this issue and are about to mitigate membrane fouling. Furthermore, this technology can reduce energy consumption due to the acclimatization of the system to solar power. Elements recovery is another gate to decrease general costs and it helps the sustainability of exploiting membrane technology. Table 1 illustrates the diverse application of membranes in various fields.

The membrane is a semipermeable barrier that allows solutes smaller than the pore dimensions to penetrate, while the particles larger than the pore extent are kept back (Valdez, 2012). Various pores are being used to remove contaminations, and the membrane can be modified to get the best result. Membranes are made from nanomaterials (Shahcheraghi et al., 2022), polymer-based films, ceramics, etc.

Table 1: Application of membranes in various fields

Application	Explanation	References
Desalination	The Reverse-Osmosis technique, advanced with chlorine-resistant membranes, is a sustainable method for treating municipal wastewater and brackish seawater. Besides, the addition of chlorination results in less fouling of the polymer-based membranes. This method hits the point of 99% salt removal from saline waters. There is another technique named Electro-desalination. This method applies charged polymer-based membranes to capture cations from the water while the anions transition is not blocked.	(Alam et al., 2021; Honarparvar et al., 2021; Meng et al., 2021)
Extraction	Using electromembranes to extract various valuable materials is being expanded. Applying positive and negative charged polymers on membranes enhances the extraction quality while decreasing the fouling rate. Moreover, this method helps eliminate hazardous elements like Uranium from seawater and could be used to separate acids and bases. The other new technology is the emulsion liquid membrane. Extraction of heavy metals like lead, hafnium, and other materials using special dilutes, acids, and surfactants show their high performance.	(Bolne et al., 2021; X. Feng et al., 2021; Hansen et al., 2021; Hansen & Pedersen-Bjergaard, 2021; Masry et al., 2021)
Nitrogen Recovery	Removing nitrogen from wastewater is an urgent need because it causes severe diseases in human body, however, recovering nitrogen is two birds with one stone. Recovering ammonia from wastewater via applying membrane gas extraction technology helps the nitrogen recovery and sustainability of the nitrogen cycle. Moreover, maintenance of high PH during the process reduces inorganic membrane fouling. Another choice for nitrogen recovery is polymer-based membranes. This method shows 99% efficiency. Electrokinetic technologies are a new solution to nitrogen extraction. Monitoring pH using electrochemical techniques results in more minor chemical needs and high ammonia removal. Nano-based membranes and ceramic membranes are proved to be effective as well.	(Adam et al., 2021; Ardebilipour et al., 2023; Brennan et al., 2021; T.-L. Chen et al., 2021)
Phosphorous Removal	A blender of membrane bioreactor technology and electromembranes results in a high-efficiency phosphorous removal from wastewaters. The antifouling resistance was enhanced by adding carbon to the system. This technology has successfully reduced the rate of membrane fouling. Another device for phosphorous removal is the application of nanocomposites besides membrane technology. These nanomaterials could selectively eliminate phosphorus Ions from water.	(Huang et al., 2021; Mendes Predolin et al., 2021; Zahed et al., 2022; Zheng et al., 2021)
Drug Release Control	Capsule membranes with determined permeability have been developed and designed to control drug release.	(Bielinski & Kaoui, 2021)
Dialysis	Dialysis is a vital need for patients who have developed end-stage renal disease. Polymer-based, especially cellulose-based membranes, have shown high efficiency in the field of dialysis. This technology is applied for patients' blood refinement and can reduce the inflammation probability.	(Ashraf et al., 2021; Azhar et al., 2021; Claudio-Gonzalez et al., 2021; Herič et al., 2021)
Distillation	Membrane distillation is a wildly used technology for desalination purposes and the generation of clean water. Penetration of water into the membrane pores is called wetting. Wetting has been a disadvantage of this system; however, new distillation technologies have overcome this issue. Using solar energy to supply the necessary heat is a green method to mitigate energy consumption. The addition of nanomaterials to the membrane system enhances the performance. Applying this technology on a large scale is still impossible due to some challenges, but a few steps forward will solve drawbacks.	(Abdel-Karim et al., 2021b; Bin Bandar et al., 2021; Ghim et al., 2021; Gontarek-Castro et al., 2021; Razaqpur et al., 2021; W. Wang et al., 2021)
Pathogens Removal	Removing pathogens is of concern in biotherapeutic products and water treatment, especially pharmaceutical wastewaters. Using membrane filtration developed with nanomaterials enhances the efficiency of pathogen removal. Newly developed membrane bioreactors with electrochemical properties have hit the point of 100% pathogens disinfection efficiency. Moreover, the electric field leads to less fouling.	(Ayano et al., 2021; Branch et al., 2021; M. Chen et al., 2021; Jacquet et al., 2021)

Metal membranes are another choice. The most common materials include cellulose, polysulphone (charged and uncharged), polyamides, and several polymer-based materials with beneficial chemical and physical resistance. Most of the materials are hydrophobic. Hydrophobic membranes are less resistant against fouling in contrast to hydrophilic ones, as hydrophobic interaction is most common among foulants (materials causing the fouling) and membrane (Choi et al., 2002). Among these materials, cellulose fibers have some drawbacks, such as moisture absorption, quality inconstancy, insufficient thermal stability, and poor compatibility with the hydrophobic polymer matrix (Sulastri & Rahmidar, 2016). In an experiment, waste banana stems with high cellulose content were successfully converted to membrane biofilter, which could act as an excellent microfilter for the lead (Pb) removal process (Sulastri & Rahmidar, 2016).

Membranes in industrial wastewater treatment

Membranes have vast applications in several industries. Removing pharmaceutical pollutants and various kinds of dye contaminants, separating oil and salts from waters, and municipal wastewater treatment are vitally dependent on membrane technology. Further, COD and BOD reduction is another successful application of these sustainable systems. Table 2 summarize its application in wastewater treatment of various industries.

Table 2: Application of membranes in industrial wastewater treatment

Industry	Explanation	References
Pharmaceutical industry	Non-bio-degradable components of pharmaceutical sewages jeopardize human health. Anaerobic membrane bioreactors show 99.97% efficiency in treating pharmaceutical wastewaters. Charged membranes have a high wastewater disinfection efficiency. The addition of humic acid to the system dwindles the fouling rate.	(Arcanjo et al., 2021; Ganzenko et al., 2021; Hussein & Al-Bayati, 2021; Kim et al., 2021)
Textile industry	Polymer-based membranes and biofilm-membrane bioreactors are good candidates for treating textile sewage. The addition of graphene oxide and tungsten oxide makes the process easier. Photocatalytic MBRs are hybrid systems capable of color removal up to 70%.	(Orhon et al., 2021; Sathya et al., 2021; Silva et al., 2021; G. Yang et al., 2021)
Municipal wastewater	Municipal wastewater contains a wide range of contaminants. Decontamination of such polluted sewages demands precise systems. Ceramic MBRs, anaerobic MBRs, thin-film nanocomposite membranes, and direct filtration are highly effective in this field.	(Caroline Ricci et al., 2021; Hube et al., 2021; R. Li et al., 2022; Qiu et al., 2021; Sun et al., 2021)
Food industry	The membranes system is wildly used in the food industry, especially in the dairy, fruit juice, sugar, beer, and wine industries. Desalination and demineralization of whey, deacidification and fruit juice concentration, stabilization of wines, and demineralization of sugar depend on membrane technology.	(Charcosset, 2021; Mahat et al., 2021; Muro claudia, 2012)

For instance, textile industries consume water more than other industries, and the produced wastewater is full of various pollutants that should be treated before being discharged. Among its positive points is that applying membrane technology seems to be more efficient and has more advantages in contrast to conventional methods. (Abdel-Karim et al., 2021a; Choerudin et al., 2021; Ćurić et al., 2021; El Morabet et al., 2020; Rostam & Taghizadeh, 2020; X. Yang et al., 2021). Using membrane technology with the biological wastewater treatment process has several advantages. For instance, less occupied space, higher biomass concentrations, reduced quantities of excess sludge, and the particulate-free and partially disinfected effluent (Fane, 1996). Due to the rapid development of the pharmaceutical industry in recent years, wastewater contamination has become a significant issue (Botero-Coy et al., 2018). Another advantage of MBR systems in contrast to CAS that is worth noting is the fact that they can operate with higher concentrations of solids (mixed liquor suspended solids - MLSS). MBRs potently treat industrial and municipal wastewater with MLSS range over 12 g/L, while CAS can only work at about 2 to 3 g/L (Asante-Sackey et al., 2022), (Karim & Mark, 2017). Thus, it is crucial to find effective pharmaceutical wastewater treatment technologies. Antibiotics in the pharmaceutical wastewaters are potable to induce resistance in various microbial species. Resistant microbes have the potential to spread across the entire planet rapidly. This process is associated with the widespread misuse and overuse of antibiotics in humans, animals, and agriculture (Botero-Coy et al., 2018; F. Wang et al., 2022).

An environmental and health concern has been recently risen as a result of the large number of trace organic contaminant (TrOCs) in urban wastewater and water bodies impacted by sewage. Due to the ineffectiveness of conventional secondary wastewater treatment processes, it is one of the most challenging aspects of wastewater treatment and reuse to effectively remove trace organic contaminant (TrOCs) such as pharmaceuticals, pesticides, steroid hormones, industrial chemicals, and ingredients of personal care products (Asif et al., 2019). Researchers have recently shown interests in the development of a wastewater treatment process for potent removal of TrOCs on account of TrOCs detrimental effects to aquatic ecosystems and human health. In line with this issue, extensive studies have been conducted on membrane bioreactors (MBRs) on the pursuit of producing effluent with a high-quality that may be potentially used for water reuse applications (Phan et al., 2015).

The high cost of MBRs is their main drawback compared to the conventional activated sludge process (CAS). These are the costs related to the membranes, pumping and aeration energy, and operations for system maintenance (Bera et al., 2022).

At the first sight, the high cost of MBRs might seem to be the biggest issue. Indeed, cost analysis has proven that in the long term, investment on MBRs would literally be more economical and worthwhile relative to conventional wastewater treatment technologies. There is plethora of rational reasons for this including decreased energy and water consumption, production of high quality effluent with a small footprint, and also cost benefits associated with water recycling, e.g. selling or reusing treated effluents for irrigation, industrial process water, or other purposes (Sharma et al., 2022).

Membrane Bioreactor (MBR)

MBRs have played a hybrid membrane role during the past couple of decades and surpassed conventional water treatment processes. For instance, they can better cope with vacillations in effluent flow rates and cause a higher effluent discharge range for recycling (Obotey Ezugbe & Rathilal, 2020). Compared to conventional systems, MBRs save much space (Radjenović et al., 2008). MBR also exploits the membrane filtration system and biological-activated sludge technology together. It has recently become more popular and putative to treat many types of wastewaters. Most recent studies demand that MBR is a sustainable treatment due to the capability of nitrification, denitrification, and phosphorus removal (table1). The earliest and most prominent application of MBRs is municipal wastewater treatment (Al-Asheh et al., 2021; Drexler & Yeh, 2014). One of the crucial membrane technology applications in the industry is treating heavily-loaded wastewaters like oily wastewaters (Zalum et al., 1994). MBRs have been studied as a technology for treating antibiotic pollution (Z. Chen et al., 2020). Studies of wastewater treatment indicate that the MBR technology can remove up to higher than 90% of chemical oxygen demand (COD) and biological oxygen demand (BOD) (Deschamps et al., 2021; Fan et al., 2021; Kong et al., 2021b; Saidulu et al., 2021; Verhuelsdonk et al., 2021). The application of new technologies in MBRs can improve the efficiency of this method. For instance, Siddiqui et al. have designed a new dynamic membrane bioreactor with anaerobic and self-forming features; this developed bioreactor is cost-effective, more resistant to fouling, and has a better function (Siddiqui et al., 2021). Another research has creatively exploited microalgae in bioreactor technologies to improve the performance and has successfully removed carbon and other contaminants (Ashadullah et al., 2021; Gao et al., 2021). Scientists demand that a combination of oxidation method and membrane bioreactor technology successfully remove contaminants from pharmaceutical and industrial wastewater (Rostam & Taghizadeh, 2020). Schneider et al. believe that compounding ozonation to the membrane bioreactors can mitigate the toxicity level and reduce micropollutants in sewage (Schneider et al., 2020).

Challenges

One of the most critical issues affecting membrane filtration, which decreases the membrane performance and dwindles membrane life, is the matter of fouling. Membrane and its interaction with the mixed liquor causes fouling, which is one of the main limitations of the MBR procedure (Zangeneh et al., 2020)

According to Kamali's research, the properties of a membrane have a crucial effect on the fouling process. Even though polymeric membranes are suitable for industrial application due to their low production costs, they may foul in a short time, resulting in system collapse. However, the application of surface modifiers could overcome this problem. Fouling is the principal obstacle restricting the usage of MBRs (figure 1). Even though ceramic membranes have solved this problem, they are still expensive materials for regular use. Hence, besides environmentally friendly substances, the development of cost-effective methods can significantly push such membranes for quick commercialization. Beyond the importance of expenses, social standards like noise, stink, visual effects, and social acceptance influence the extensive application of membrane technologies in sewage treatment (Kamali et al., 2019). The combination of rotating biological contactor and membrane bioreactor [RBC-MBR] can be seen as a new energy efficient wastewater treatment process. Rotating biological contactor (RBC) is an established attached growth process for remediation of organics pollutants (Waqas et al., 2020). The potential advantages of RBC in comparison to conventional activated sludge (CAS) and trickling filter are its simplicity and ease in monitoring, low operational and maintenance costs, high biomass concentration, short hydraulic retention time, high oxygen transfer efficiency, no sludge recirculation, resistant to shock and toxic loads, making it a suitable process for wastewater treatment (Waqas et al., 2020). And, nanofiber membranes are characterized by their high surface area, nanosized pores, and high porosity. The efficiency of filtration and separation of particulate materials has been improved by nanofiber membranes (K. Wang et al., 2018). Furthermore, Metal Organic Frameworks (MOFs) have potential to use as an adsorbent for EC removal from wastewater due to their large pore surface area, high porosity, pore size, and surface functionality (Dias & Petit, 2015). Recently, fabrication of MOFs-based bio nanocomposites have gained an increasing attention for wastewater treatment applications (Butova et al., 2016), (G. Li et al., 2020). Several applications of MOFs in wastewater treatment have been deeply reviewed by Furukawa et al., 2013; Dhakshinamoorthy et al., 2018; Kumar et al., 2018; Mon et al., 2018; Bedia et al., 2019; Rego et al., 2021; Wang Q. et al., 2020 (Furukawa et al., 2013), (Dhakshinamoorthy et al., 2018), (Kumar et al., 2018), (Mon et al., 2018), (Bedia et al., 2019), (Rego et al., 2021), (Q. Wang et al., 2020). However, MOFs real industrial applications have been poorly explored (Kumar et al., 2018). The industrial utilization of MOFs in wastewater treatment could be limited by their intrinsic instability which means that they may collapse in aqueous environments (Rego et al., 2021), (Russo et al., 2020).

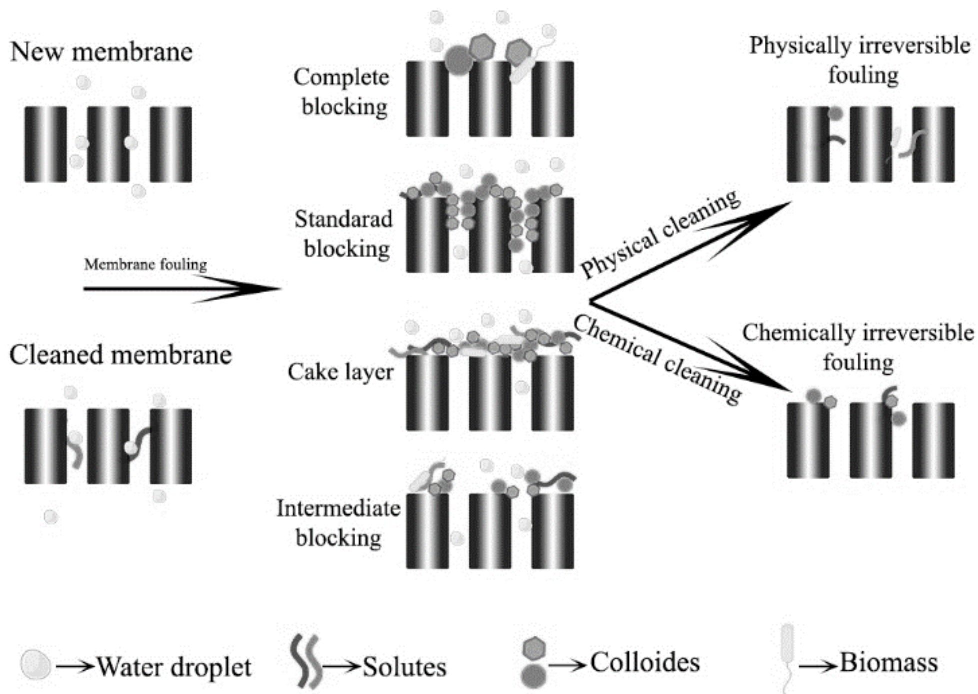

Figure 1. The illustration above renders the membrane fouling process and four types of pore blocking. The effectiveness of physical and chemical cleaning is shown on the right side of the picture. Physical cleaning detaches foulants from the surface of the membrane, and chemical cleaning removes refractory contaminants, especially from the walls. Despite cleaning, permanent pollutants will remain stuck on the surface or inside the pores.

Selection of the best material for a particular membrane needs perfect considerations, for example, expenses, dangers of membrane plugging, and cleaning. Feed quality, membrane features, and filtration circumstances are the most critical parameters for successful membrane filtration.

Sorts of membrane fouling:

a) Complete blocking: obstruction of the pore through a particle larger than the pore size.
b) Standard blocking: reduced pore size due to deposition of multiple smaller particles on the pore walls.
c) Intermediate blocking: obstruction of the pore by several particles accumulating on each other
d) Cake layer: deposition of larger particles on the pore's surface (Choi et al., 2002).

Sorts of fouling from the practical aspect:

1. Contaminant particles can be eliminated from the pores by physical scrubbing. It happens

2. When foulants are only stuck on the surface of the membrane. These particles form a cake layer that prohibits water penetration into the membrane.
3. Permanent fouling is detached by chemical cleaning. It happens when foulants are deposited on the walls of the pore.
4. Permanent fouling, which is not scraped by simple cleaning (Kamali et al., 2019) (figure 1)

Another challenge we encounter is the probability of chemical and biological terrorism, which needs enormous attention (Zhou et al., 2014).

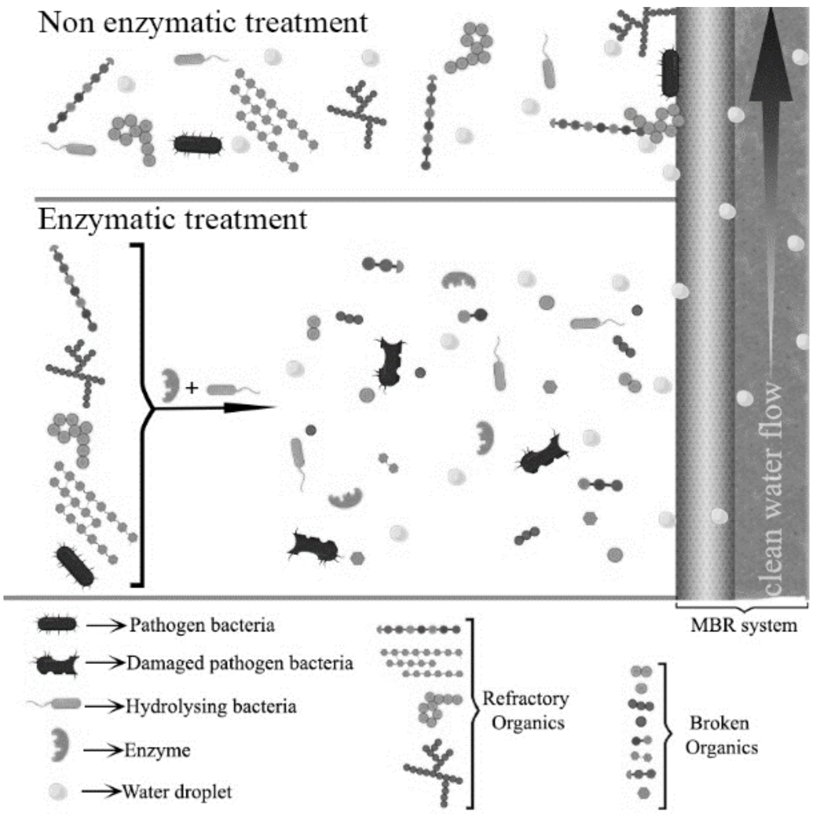

Figure 2. This process shows the effectiveness of compounding enzymatic reaction to the filtration system. These enzymes break down the stubborn organics and expedite the filtration process.

Industrializing a technology and applying it on a large scale requires many considerations. We need all advantages compiled to complete the process and introduce this technology for the public use. For instance, anaerobic membrane bioreactors (AnMBR) seem to have a bright future for presenting more applicable methods. AnMBRs have overcome the high levels of energy consumption in contrast to conventional methods and are cost-effective. Moreover, they are more effective and powerful in removing methane, capable of producing biogas, and have acceptable biological efficiency. AnMBRs may cause adverse environmental effects if suitable downstream processes are not applied despite all these advantages. Another drawback is the removal of sulfur from the downstream system. Sulfur releases nasty odors and toxic components and causes fouling; however, several studies have focused on this matter and achieved new methods to mitigate the rate of fouling. These substantial obstacles hinder this technology from being vastly used, although it has many other advantages. Nevertheless, AnMBRs technology has a high potential to overcome weaknesses and build up a sustainable future (Kong et al., 2021a; Lei et al., 2021; C. Schneider et al., 2021; Shahid et al., 2020; Shin et al., 2021; Sohn et al., 2021; Zhang et al., 2021).

Although MBR is suggested as one of the most applicable technologies for the removal of refractory organics, there are still non-biodegradable compounds that have to be treated with chemical methods. In the interest of this matter, advanced oxidation processors are in need (Neoh et al., 2017).

Discussion and Future prospects

MBRs advanced with additives render a high function and discharge a high-quality effluent. Bioaugmented membrane bioreactors are advanced technologies capable of increasing the microbial community that can remove hazardous and recalcitrant components from coking wastewater. Moreover, they are more efficient in mitigating chemical oxygen demand than conventional membrane filtrations (Zhu et al., 2015). Dynamic MBRs adopted by proteases are another solution to reduce refractory organics. Besides, the addition of protease catalysis could dwindle the pathogen community while speeding up the growth of bacteria that hydrolyze polysaccharides and polypeptides. Protease catalysis is a method to increase the release rate of volatile fatty acids (VFA) from leachate. It has been investigated that low-biodegradable and stubborn organics are broken down to degradable particles and VFA after using a higher concentration of enzymes. On the other hand, a dynamic membrane retains proteases and substrates for a long while and prolongs the reaction time (Liu et al., 2018) (figure 2).

It is worth mentioning that newly developed eco-green MBRs have a high potential to remove toxic dyes from textile wastewaters. In a study, scientists applied fungi and biopolymers instead of chemicals to resolve solute dyes (Dayı et al., 2020). The addition of H_2O_2 and microwave rays to MBR filtration is another functional method to clean stubborn compounds (Alvarino et al., 2016; Chen et al., 2020; Gu et al., 2019). Less complex and more eco-friendly techniques can be found to dwindle refractory organic compounds. Novel MBR refers to a membrane bioreactor system inoculated with common baker's yeasts, which affects recalcitrant organics of leachate and mitigates membrane fouling (Brito et al., 2019). From another perspective, other methods can be combined to produce a more favorable wastewater treatment system. Applying ZELIAC is shown to be functional for heavy metal elimination. Although this method is applied to sequencing batch reactors (SBR), it is able to improve other wastewater treatment systems such as MBRs as well (Mojiri et al., 2016).

Membranes have another application in which they act as a drug releaser. In membranes manufactured at a fixed long distance, a high drug release was observed because of the high porosity. This fact proved that the drug-containing membrane could be rapidly degraded, in contrast to the membrane made at a short distance that had a slower drug release rate (Park et al., 2015).

As the largest producer of textile products, China has to treat a large amount of wastewater discharged every year. By applying MBR technology for textile wastewater treatment, China has shown the high benefits and potential of membrane bio-reactors to the world. Less land usage, individual treatment potential, high performance, less sludge production, high-dense effluent treatment, less energy consumption, cost-effectiveness, and sufficient contaminant removal are the advantages of this technology, yet, there are a few steps to the feasibility of MBRs in large scales (Chen et al., 2021; Gao et al., 2021; Li et al., 2020; Zhang et al., 2021).

New studies bespeak additional benefits besides wastewater treatment. Yadav et al. suggest recovering the resources from wastewater and changing the economy type from linear to circular.

They demand that this might reduce the energy loss and recover valuable materials (Noriega-Hevia et al., 2021; Yadav et al., 2021).

There are several opportunities for pharmaceutical wastewaters. These pollutants are not biodegradable, so using the classical biological treatment is inefficient in removing these compounds. Thus, several methods are needed to treat these components (table2). Furthermore, new studies have considered the potential of biological systems to treat pharmaceutical contaminants. Researchers have applied bioreactors to remove pharmaceutical wastes from municipal wastewaters successfully. It is worth noting that some of them have added fungi to the membrane-bioreactor system to advance the performance. (Dalecka et al., 2021; Femina Carolin et al., 2021; Hosseinpour et al., 2021; Olicón-Hernández et al., 2021; Tiwari et al., 2021; Tormo-Budowski et al., 2021; H. Zhang et al., 2021)

The preparation of inorganic membranes that have less thickness is another opportunity in water processing. These membranes have an excellent position for delivering material, as they are energy efficient with significantly reduced expenses of the process. The main challenge of the inorganic membranes system is its application on large scales. (Goh & Ismail, 2018). There are optimisms for further reduction in the costs of MBRs, enhanced pollutant removal, and more feasibility in various industries (Zhao et al., 2019).

The best practice in global-class water and wastewater treatment using Membrane Bioreactors (MBRs) involves the integration of membrane technology with biological systems and even biological engineering, resulting in enhanced treatment efficiency and the removal of challenging contaminants. MBRs demonstrate superior performance compared to conventional systems, delivering high-quality effluent that meets stringent standards. Their compact design allows for efficient use of space, making them suitable for large-scale applications even in limited areas. Considering economic feasibility is essential, with an analysis of factors such as energy consumption, membrane fouling, and maintenance costs. By exploring diverse applications across municipal, pharmaceutical, and industrial sectors, MBR technology proves its versatility and efficacy. Through evidence-based examples and case studies, understanding these best practices can support the wider adoption of MBRs as sustainable and efficient solutions for global water and wastewater treatment.

It is worth mentioning that CRISPR technology, known for its revolutionary gene editing capabilities, holds the potential to enhance Membrane Bioreactors (MBRs) technology in several ways. Here are a few ways in which CRISPR can contribute to improving MBRs:

1. Targeted Microbial Community Engineering: MBRs rely on the activity of microorganisms to degrade and remove organic compounds from wastewater. CRISPR technology can be utilized to engineer specific microbial communities with enhanced metabolic capabilities, such as increased tolerance to toxic compounds or improved degradation efficiency. By selectively editing the genes of microorganisms, researchers can optimize their performance within the MBR system, leading to more efficient and robust wastewater treatment.

2. Enhanced Resistance to Membrane Fouling: Membrane fouling, the accumulation of particles and microbial biofilms on the membrane surface, is a common challenge in MBRs. CRISPR technology can be employed to modify the genes of microorganisms to reduce the production of extracellular polymeric substances (EPS), which contribute to membrane fouling. By targeting specific genes involved in EPS production, researchers can engineer microorganisms that produce less fouling material, thereby reducing membrane fouling and improving the overall performance and lifespan of the MBR system.

3. Phage Resistance: Bacteriophages, viruses that infect bacteria, can pose a threat to the stability and performance of MBRs by infecting and lysing the beneficial microorganisms responsible for

wastewater treatment. CRISPR technology can be used to introduce phage-resistant genes into microorganisms present in the MBR system, providing them with an enhanced defense mechanism against phage attacks. This approach helps maintain a stable microbial community and prevents disruptions to the wastewater treatment process.

4. Contaminant Removal: CRISPR technology can be utilized to engineer microorganisms with enhanced capabilities for contaminant removal. By introducing genes encoding specific enzymes or transporters, researchers can enhance the ability of microorganisms to degrade or remove specific pollutants, such as recalcitrant organic compounds or heavy metals. This targeted gene editing approach can potentially improve the overall efficiency and effectiveness of MBRs in treating complex industrial wastewater streams.

It is worth noting that valuable research are being conducted to investigate the significant effects of CRISPR technology on enhancing the wastewater treatment capabilities of certain microorganisms. For example, Feng et al. successfully employed CRISPR technology to modify the traits of *Dunaliella salina*, resulting in increased biomass and improved functional efficiency (Feng et al., 2020).

It's important to note that the application of CRISPR technology in MBRs is still in its early stages, and further research and development are required to fully harness its potential. Nonetheless, CRISPR holds promise as a tool to optimize MBR systems in explained fields, leading to more efficient and sustainable wastewater treatment.

Conclusion

This review highlights the significant applications and advantages of membrane technology in wastewater treatment. Membrane Bioreactor (MBR) technology stands out for its superior performance and sustainability compared to conventional wastewater treatment systems. MBRs offer a promising solution for addressing water management challenges, thanks to their compact design, efficient treatment capabilities, and potential for resource recovery.

Looking to the future, the integration of CRISPR and biological engineering holds tremendous potential to further enhance MBR technology. Leveraging the power of CRISPR technology, researchers can target genetic modifications in microbial communities within MBRs, resulting in improved pollutant degradation, enhanced membrane fouling resistance, and more efficient nutrient removal. Additionally, adopting biological engineering principles can optimize MBR design and operation, leading to enhanced performance and cost reduction. However, ethical considerations associated with genetic modifications should be carefully addressed.

To advance MBR technology, future research should focus on optimizing MBR operation, reducing costs, and conducting comprehensive economic analyses. Overcoming these challenges will facilitate the global-scale adoption of MBRs, revolutionizing wastewater treatment practices and contributing to a more sustainable future.

However, several limitations still need to be addressed to enhance the practical functionality of MBR systems. Firstly, there is a notable lack of sufficient investment dedicated to improving MBR systems, hindering their overall performance and widespread adoption. Additionally, efficient removal of heavy metals from wastewater remains a challenge, necessitating further research and development. Furthermore, achieving higher levels of efficiency in removing wastewater nutrients, such as nitrogen and phosphorus, requires innovative solutions. The use of microorganisms, particularly modified ones, in MBRs can potentially lead to the production of hazardous byproducts, highlighting the importance of careful monitoring and control measures. Moreover, fostering collaboration between universities, research groups, and industries is essential to leverage the expertise of professionals and strengthen the understanding of MBR technology. These limitations emphasize the significance of collaboration, investment, and ongoing research to overcome challenges and maximize the effectiveness of MBR technology in wastewater treatment.

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