



Current status of hybrid membrane reactors and processes for wastewater treatment: a review

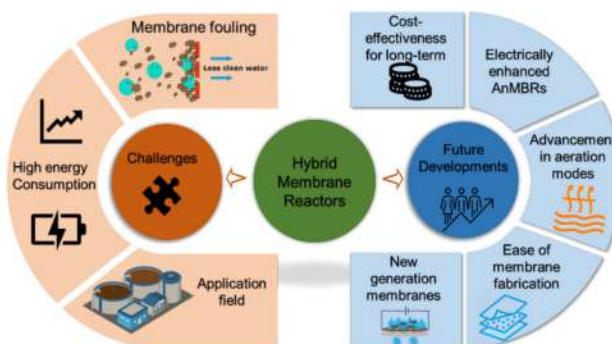
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Abstract

Wastewater treatment technologies are now being progressively utilized as establishments capable of facilitating the recovery of vital resources such as water, nutrients, and energy for advantageous use and reuse. The membrane technology, a well-established municipal and industrial wastewater treatment method, has gained significant recognition worldwide. However, there are still hurdles to overcome, such as higher energy consumption and fouling of membranes. Recent progress in developing hybrid configurations for advanced membrane technology has been studied to address these challenges. This paper explores the advancements in hybrid membrane reactors and processes, including arrangements as well as combinations with other technologies. Specifically, the membrane bioreactor has effectively integrated with advanced oxidation and/or separation approaches to treat municipal and industrial wastewater. Furthermore, the hybrid photocatalytic-membrane process has introduced permeability, hydrophilicity, rejection, antifouling, and photodegradation effectiveness, resulting in efficient wastewater removal techniques. Integrating electrochemical processes with membrane bioreactors has also drawn attention, particularly for parallel improvement in removal efficiencies, and helps mitigate foulant deposition into the membrane. Advanced oxidation processes have become an essential component of industrial wastewater treatment, particularly for contaminants of greater concern. The paper further discusses feasible combinations of advanced oxidation methods and possible future development paths for hybrid membrane systems.

Graphical abstract



Keywords Membrane technology · Membrane bioreactor · Photocatalytic membrane reactor · Electrochemical membrane bioreactor · Advanced oxidation processes

Introduction

Water is the most common resource on the planet and the most prevalent molecule in living things. The lack of fresh water supply and the management of wastewater are two

Extended author information available on the last page of the article

of the biggest obstacles to sustainable development in the twenty-first century (Egea-Corbacho et al. 2023; Kusumitha et al. 2019; Majumder and Gupta 2020). Over the past century, the amount of water used worldwide has grown by a factor of six, and by 2050, the amount of water needed will have gone from $4600 \text{ km}^3 \text{ y}^{-1}$ to almost $6000 \text{ km}^3 \text{ y}^{-1}$ (Qi et al. 2020). As a result, a significant amount of wastewater is also produced. Wastewater with high amounts of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN), total suspended solids (TSS), etc., is a result of a variety of human-induced activities (Majumder et al. 2021; Qi et al. 2020). In recent years, great focus has been placed on eliminating different emerging pollutants from wastewater, such as pharmaceuticals, disinfectants, dyes, chemical reagents, etc. Therefore, several physical, chemical, and biological treatment strategies and their combinations have been developed during the past few decades to deal with such pollutants.

Wastewater reuse is a promising trend that is being used to address this problem as a result of the scarcity of precious freshwater resources. It is seen as being crucial to the Sustainable Water Management Programme. High-performance and reasonably priced wastewater treatment systems must be put in place. Inappropriate treatment of wastewater from industries and houses before disposal leads to severe environmental and health issues in the surrounding communities (Qi et al. 2020). Additionally, wastewater treatment plant facilities, hospitals, municipal sewage systems, industrial wastewater, run-off water from agricultural land, and others continuously contaminate freshwater basins, posing a serious threat to the ecosystem (Majumder and Gupta 2020). Urban sewage or industrial treatment facilities are more likely to be locations where antibiotics and antibiotic-resistant genes (ARGs) are released into the environment (Babu Ponnusami et al. 2023).

An advancement has been made in membrane technology for wastewater treatment and recovery. As a novel separation and purification technology, membrane technology has been widely applied and plays a unique role in a variety of pollutants, such as the dyestuff industry, seawater desalination, oily industrial wastewater treatment, and brackish water desalination (Yue et al. 2018). Growing interest has been shown in membrane technology due to its many benefits over traditional activated sludge treatment processes, including its lesser environmental impact, increased separation efficiency, lower sludge production, and significantly higher effluent quality (An et al. 2023). The existing conventional wastewater treatment plants in developing nations will be impacted by the rapid growth in population, which will result in overburdened quality and quantity of pollutants and a lack of room for the development of the existing treatment plants (Samaei et al. 2023). Applications of membrane technology provide technological solutions for environmental

protection, greener production, reuse efficiency, and challenges with separation and purification (Yue et al. 2018).

However, their potential uses have been constrained due to the antifouling limitation and the permeability-selectivity trade-off. Membranes lack selective separation of the salts and contaminants, and have large operation and maintenance costs (Yue et al. 2018). Only once the proper pre-treatment is applied is the membrane separation process feasible. Backwash water must be used in part of the produced water, and this backwash water must be mixed with the influent water. If the coastal discharge is unavailable, disposing of RO rejects with highly dissolved solids can be problematic (Padaki et al. 2015). The combination of membrane reactors with other technologies can be seen as a safer "multiple-barrier approach" to wastewater treatment, given the limitations of membrane technology. The hybrid membrane reactor's goals are to increase the efficacy of discharged permeates, reduce membrane fouling, and increase the stability of the treatment process (Mahlangu et al. 2023; Rostam and Taghizadeh 2020).

Membrane bioreactor (MBR) technology includes high effluent quality, small footprint, complete separation of hydraulic retention time (HRT) and solids retention time (SRT), etc., whereas a major weakness resides in energy consumption owing to membrane fouling. By increasing the volume loading rate of the influent and/or the load that the current plants can handle, MBR systems make it possible to modify conventional activated sludge processes (ASP), and they also can retain small molecular weight organic micro-pollutants (Sonawane and Murthy 2023). MBR with ultra-filtration (UF) membrane is also able to retain some types of viruses. In this manner, expanding municipalities could address the issue of wastewater treatment plants' inadequate input capacity due to the anticipated population development. Furthermore, new facilities using MBR systems would require much less area than plants using activated sludge, and this wastewater treatment technique generates permeate suitable for direct reuse (Gao et al. 2023). The effects of membrane fouling, elimination of recalcitrant chemicals, and removal of color and metal compounds were all more effectively reduced by combining a membrane bioreactor with advanced oxidation processes (AOPs) (Amini et al. 2020; Jiang et al. 2017).

Due to the high energy consumption of the electrochemical membrane reactor, combining the process with the membrane could result in a more effective method for treating pollutants. In an electrochemical cell coated with a catalyst, conductive membranes serve as the cathode and the anode, speeding up the breakdown of pollutants (Hossein-zadeh et al. 2015). Advanced oxidation processes (AOP) are thought to be effective ways to simultaneously extract and degrade a variety of non-biodegradable organic compounds from water (Babu Ponnusami et al. 2023; Hodges et al.



2018). Among AOP, heterogeneous photocatalysis employing semiconductor catalysts such as TiO_2 , CdS , SnO_2 , WO_3 , SiO_2 , ZrO_2 , ZnO , Nb_2O_3 , Fe_2O_3 , SrTiO_3 , GaP , and ZnS is the most popular one. Also, AOPs such as peroxone ($\text{O}_3/\text{H}_2\text{O}_2$), ozonation, UV, photo-Fenton, photocatalysis, electrochemical advanced oxidation processes (EAOPs), etc., have been successfully incorporated with membrane separation for removal of pharmaceuticals and textile dyes from water (Ganiyu et al. 2015).

This research examines the current state and possible uses of several membrane reactor systems including MBRs, photocatalytic membrane reactors (PMR), electrochemical membrane reactors/bioreactors (eMBR), and advanced oxidation and reduction processes combined with membrane reactors/bioreactors. It presents a comprehensive review of various hybrid technologies, including their configurations, modes of operation, the materials and modules employed, membrane fouling, and fouling-related characteristics. Some of the most recent breakthroughs, future prospects, and hybrid membrane reactor research are discussed with theoretical guidance, in-depth descriptions of both common and novel configurations, and a detailed overview of the development of hybrid membrane reactors in wide engineering applications for wastewater treatment.

Membrane bioreactors

Membrane bioreactor (MBR) systems are frequently employed in place of conventional wastewater treatment systems as an upgrade or retrofit (Luo et al. 2016). Over time, MBR has gained significant academic interest and seen rapid expansion in practical applications across the globe (Krzeminski et al. 2017). The number of large-scale ($10,000 \text{ m}^3 \text{ d}^{-1}$) and super-large-scale ($100,000 \text{ m}^3 \text{ d}^{-1}$) treatment facilities going into operation has increased, and the MBR technology is claiming a sizable portion of the wastewater treatment market. MBRs have grown in popularity as a very effective wastewater treatment technology that combines biological treatment with membrane separation for the treatment of municipal and industrial wastewater. Activated sludge and membrane separation processes are coupled in a membrane bioreactor. The reactor operates like a conventional activated sludge process; however, no subsequent clarification or tertiary treatment stages, like filtration, are necessary. MBR frequently uses low-pressure membrane filtration to remove effluent from activated sludge, such as microfiltration (MF) or UF. The primary benefits of MBR technology are high effluent quality, small footprint, wide-ranging HRT and SRT, etc. In contrast, the main weakness exists in its energy consumption, which is largely due to membrane fouling (Kumar Gautam et al. 2023).

The conventional system represents the activated sludge process, which is always preceded by primary settling. The plant itself consists of a primary clarifier, an aeration tank, a secondary clarifier, a sludge return line, and an excess sludge waste line leading to a digester. With the freedom to choose from a wide range of HRT and SRT offered by MBR technology, operating parameter controls can be adjusted with greater flexibility. In Membrane bioreactors, high sludge concentrations permit efficiency in treating high-strength wastewater (Krzeminski et al. 2017). Activated sludge, which is retained inside the bioreactor, contains solids and macromolecules combined with long sludge age; it increases the time of contact between sludge and crucial classes of substrates, allowing specialized slow-growing microorganisms to grow and remove low-biodegradable pollutants from wastewater and improve the removal of refractory compounds (Darmayanti et al. 2023).

Submerged membranes and an external circulation system, often known as a side-stream configuration, are the two main arrangements used in MBR. In a submerged MBR, the turbulence of rising air and liquid in the submerged membrane modules causes shear forces to control the cake layer formation to achieve a stable flux. Only crossflow filtration is suited for continuously separating activated sludge with high mixed liquid suspended solids (MLSS) concentrations (An et al. 2023). Submerged MBRs are often operated at low differential pressure and well below the essential permeate flux to control fouling. For designing a submerged MBR, flux heterogeneity, packing density, air scouring indicating diffuser size, gas flow rate, nozzle type, frequency, bubble size, channel gap between flat sheets, etc., as well as shear stress and its impact on extracellular polymeric substances (EPS), sludge, and membrane surface must all be taken into account. Additionally, other factors affecting submerged MBRs' functioning include backwashing, sequencing of aeration, and filtration (Sengur et al. 2015).

In the external and side-stream configuration, the required transmembrane pressure (TMP) is generally much higher than that used for the immersed configuration, and the recirculation pump confirms the required TMP in the membrane chamber. Crossflow velocity thereby permanently prevents the development of a filter cake on the membrane's surface. The crossflow velocity along the membrane surface to achieve optimum operational efficiency regarding filtration cake removal and energy demand. High shear forces cause larger sludge agglomerates and flocs to break down, reducing the biomass particle's size. Following the discharge of soluble microbial compounds, fouling, and membrane clogging may become more rapid. Clogging of membrane pores is a well-known and serious issue associated with membrane fouling (Meng et al. 2015) in MBR. However, the membrane can be cleaned without interfering with system performance, as chemical cleaning of a fouled membrane is

easier to achieve in a side-stream setup. In addition, replacing or inspecting membranes is more spartan than replacing membranes that are immersed directly into the reactor.

Hybrid membrane bioreactor

Osmotic membrane bioreactors (OMBRs)

Forward osmosis (FO) and Reverse osmosis (RO) techniques have gained interest due to their benefits, such as superior product water quality and low fouling tendency (Luo et al. 2016; Neoh et al. 2016). FO, also known as osmosis, is the process by which water is moved over a semi-permeable membrane from a location with a higher concentration of water molecules to a region with a lower concentration of water molecules through a selectively permeable membrane. The differential in solute concentrations across the membrane is what propels the transfer. Osmotic membrane bioreactors (OMBRs) are similar to MBRs in that they typically include a membrane separation unit and an activated sludge process. OMBR contains a non-porous osmotically driven membrane (i.e., FO membrane), unlike porous pressure-driven MF/UF membranes. This also results in problems such as salinity build-up, internal concentration polarization, and reverse salt transfer in OMBRs (Yue et al. 2018). The organic impurities that remain after MBR treatment are hydrophobic and can adsorb the MLSS, which prolongs the duration of the impurities remaining in the reactor and is also ineffective for removing some persistent hydrophilic residual organic contaminants. FO can also be employed as a stand-alone procedure in the agricultural sector with a drawing agent made of a concentrated fertilizer solution (Majeed et al. 2015).

Hybrid systems combine thermally driven (e.g., MD) membrane processes with FO driven by pressure, as in the case of NF and RO membranes. The FO pre-treats wastewater for draw solute recovery in these hybrid systems and provides a solution free of foulants. In contrast to treating raw wastewater directly with high retention membrane processes, FO membrane-based hybrid systems can result in a higher quality effluent and increased process efficiency. For a variety of pollutants, FO membrane-based hybrid systems are frequently referred to as a "double-barrier defense." Holloway et al., (Holloway et al. 2014, 2015) suggested a stable operation of a pilot UFO-MBR (Fig. 1a), treating raw domestic wastewater over a time of four months. Removal below the detection limit has been reported for 15 out of 20 trace organic chemicals (TrOCs) investigated in their study using a pilot RO process for draw solution and clean water recoveries (Holloway et al. 2014, 2015).

As per Nguyen et al., (Nguyen et al. 2016); the feasibility of applying attached growth biofilm (AGB) integrated with

an osmosis membrane bioreactor (OsMBR) system (AGB-OsMBR/MD) hybrid system in wastewater treatment lowers membrane fouling and enhances nutrient removal. A stable water flux of $3.62 \text{ L m}^{-2} \text{ h}^{-1}$ during a 60 day AGB-OsMBR operation and lower nitrate and nitrite concentrations in the bioreactor attributed to good denitrification in the anoxic and anaerobic zones of the biofilm layer during AGB-OsMBR operation (Nguyen et al. 2016). Due to the reverse draw solute flux and strong salt rejection by the FO membrane, salinity build-up in the bioreactor is a significant problem related to OMBR. The increased salinity in the bioreactor can alter the microbial community and reduce the driving force for water penetration, which is transmembrane osmotic pressure (Luo et al. 2016), and increase the amount of EPS and soluble microbial products (SMP) in the mixed liquor, weakening the biological treatment and causing membrane fouling.

In a study by Luo et al., (Luo et al. 2016), two ionic organic draw solutes, NaOAc and EDTA-2Na, were evaluated for their performance in the OMBR. They were found to moderate salinity build-up when compared to NaCl during OMBR operation and contribute slightly less water flux but significantly less reverse salt flux than NaCl (Luo et al. 2016). By combining osmotic processes with conventional membrane bioreactors, osmotic membrane bioreactors represent a promising breakthrough with the potential to treat wastewater, desalinate water, and recover resources. Their energy efficiency is a benefit since the hydraulic pressure created by the osmotic pressure differential across the membrane can reduce the need for pumping. Concentration polarisation can hamper osmotic flow, which is brought on by solute buildup close to the membrane. Concerns about applicability arise from the reliance on a salinity gradient between chambers (Cao et al. 2022). A study by Zhou et al., (Zhou et al. 2024) evaluated the fouling propensity of a hybrid ceramic membrane bioreactor (CMBR) RO system treating real textile wastewater over an extended period. The system achieved ~99.8% COD removal and 97.4% total nitrogen removal. However, soluble EPS caused irreversible fouling on the UF membrane. In-situ ozonation improved filterability, reducing ceramic membrane fouling but potentially increasing RO fouling due to low molecular weight byproducts. The system achieved nearly 100% removal of 20 aromatic amines, demonstrating its effectiveness for textile wastewater reclamation. Modified fouling indexes assessed RO feed water fouling potential (Zhou et al. 2024).

Membrane distillation bioreactor (MDBR)

Membrane distillation (MD) is a thermally driven separation process, mostly applied for the separation of non-volatile dissolved substances from a diluent. The process can be used for the treatment of a broad range of salinities, including



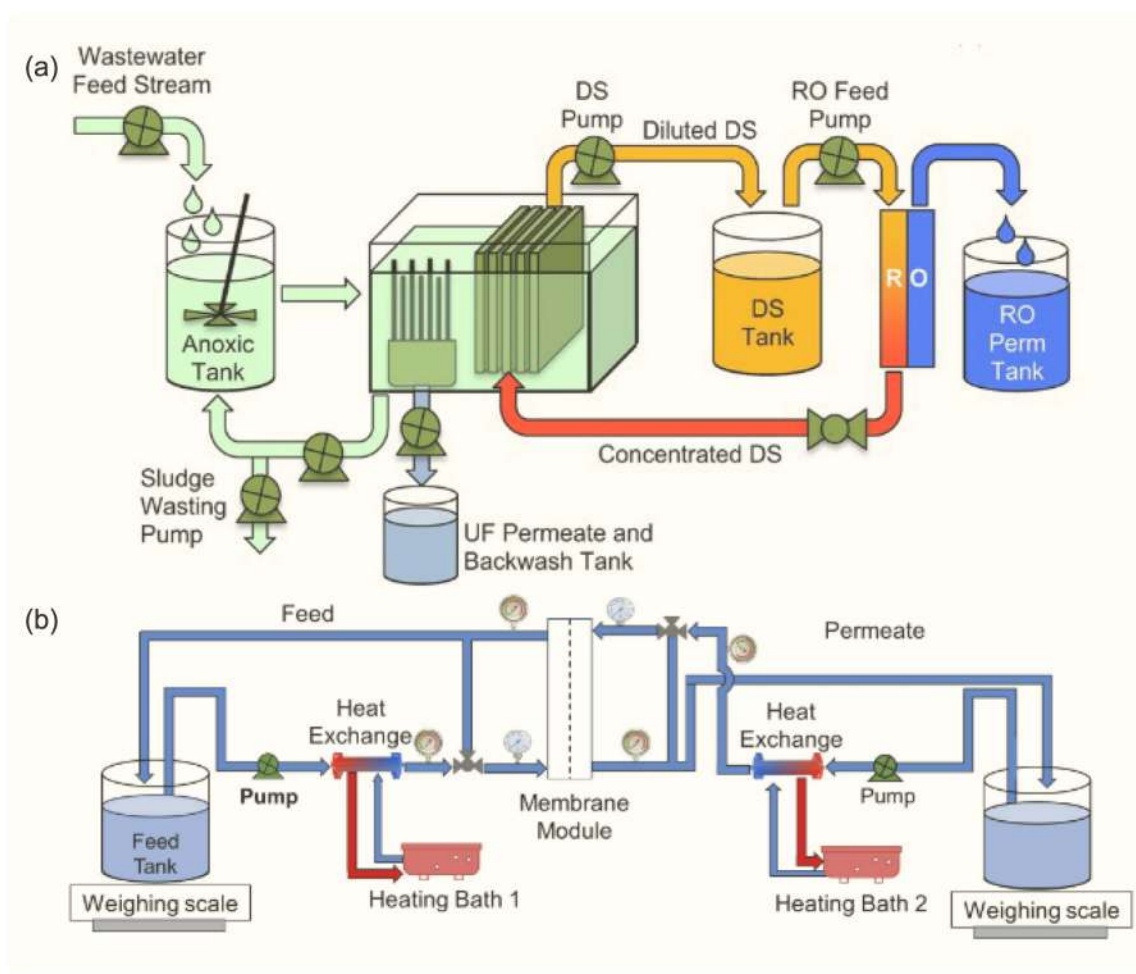


Fig. 1 Schematic of (a) The UFO-MBR system used for long-term, Reprinted with permission from Ref (Holloway et al. 2015), Copyright [2015] Elsevier B.V., and Schematic representation of the (b)

Membrane distillation setup; Modified and reprinted with permission from Ref (Lies Eykens et al. 2016a, b), Copyright [2016] Elsevier B.V

seawater desalination, brine and industrial wastewater treatment, and resource recovery up to crystallization (Nguyen and Lee 2015). Compared to traditional membrane processes for distillation and RO, MD is a relatively new technique that has been investigated globally as a low-cost, energy-saving solution. A thermophilic bioprocess and the membrane distillation process are combined in a membrane distillation bioreactor (MDBR). High-quality water is produced by the water vapor crossing a temperature gradient across a hydrophobic and microporous membrane. The transmembrane vapor pressure differential caused by the temperature difference between the feed and the permeate forces the vapors over the membrane pores from the hot side to the cold side (Naidu et al. 2020).

As per Drioli et al., (Drioli et al. 2015) the MD process can be carried out at temperatures typically below 70 °C and is driven by a low-temperature difference between the hot and cold solutions of up to 20 °C. As a result, low-grade

waste and/or alternative energy sources like solar and geothermal energy can be combined with MD systems to create a liquid separation system that is both affordable and energy-efficient (Drioli et al. 2015). When compared to the RO process, high recovery factors and high concentrations can be achieved in operation since concentration polarization has no impact on the driving force of the process. The purification, extraction, extremely high concentration, and final formulation of organic and inorganic species can all be accomplished practically using this technology in a wide range of industrial and biological operations. Since the wastewater discharged from the textile industry typically maintained the temperature at 70–80 °C, the MD process could utilize industrial waste heat without needing additional heating, significantly reducing the energy consumption during operation. Alternatively, MD can capture the heat for electricity generation using a waste heat-to-power system, and the MBR process can be powered by the generated heat,

reducing the need for fossil fuel electrical energy (Goh et al. 2015). Some of the MDBR's possible advantages are that the permeate quality is on par with the RO process and unaffected by biological activity. Because membrane separation controls permeate quality in the presence of low bioactivity in the reactor, the system may be able to withstand shock loads. Additionally, the MD process might produce reclaimed water with the same quality as what is now only possible with traditional MBR plus RO or conventional activated sludge plus MF plus RO. Furthermore, because permeate quality can be achieved without reaching a standard value for bioactivity, the start-up time should be lower than in a typical bioreactor. This hybrid process can function at low levels of biological activity (Abu-Zeid et al. 2015; Khayet 2011; Naidu et al. 2020; Rezaei et al. 2018; Tijing et al. 2015; Warsinger et al. 2015).

Eykens et al., (Eykens et al. 2016a, b), when using the same bulk driving force, their study compares the flux and energy efficiency of a lab-scale direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), permeate gap membrane distillation, and vacuum membrane distillation (VMD)(Fig. 1b). VMD experienced the largest flux, which was subsequently followed by DCMD, PGMD, and AGMD. Additionally, these various configurations are not all equally sensitive to the applied process parameters, such as salinity, flow velocity, and temperature difference. They also concluded that the configuration chosen must strike a balance between high fluxes, energy recovery, and additional investment costs for external heat exchangers, pumps, and condensers. This choice depends on the circumstances of each case and can only be made by carefully considering all pertinent factors (Eykens et al. 2016a, b). Conventional membrane distillation designs can be replaced with submerged VMD, which has higher thermal efficiency and lower energy usage, but scaling problems (Meng et al. 2015). Transverse vibration in submerged VMD increased permeate flux by up to 21% but did not appreciably reduce salt crystal deposition. The long-term operation of a study conducted by Meng et al., (Meng et al. 2015) showed that faster wetting occurred in the absence of agitation, while submerged VMD coupled with transverse vibration consistently provided higher flux for both single and mixed salt feed solutions.

In a DCMD system studied by Sanguanpak et al., (Sanguanpak et al. 2024) with a PTFE membrane (0.2 μm) treated raw and MBR-treated municipal landfill leachate at feed temperatures of 50, 60, and 70 $^{\circ}\text{C}$, with a 10 $^{\circ}\text{C}$ permeate. DCMD of MBR permeate achieved > 90% organic carbon and salt rejection but faced a higher flux decline. Fouling and volatile fatty acid penetration increased at 70 $^{\circ}\text{C}$, while optimal performance was at 50 $^{\circ}\text{C}$ with MBR permeate (Sanguanpak et al. 2024). (Le et al. 2024) integrated a hyper-thermophilic aerobic bioreactor (up to

65 $^{\circ}\text{C}$) with a tubular submerged MD system for wastewater treatment. Over 92 days, it achieved 99.5% organic, 96.4% ammonia, and 100% phosphorus removal, with 6.15–8.25 LMH fluxes. Microbial biomass increased 1.6 times despite 12,532 $\mu\text{S cm}^{-1}$ salinity (Le et al. 2024).

Due to their unique separation capabilities, MDBR holds promise in various water treatment applications. One of the advantages is their ability to produce high-purity water, making them valuable for wastewater treatment and specific industrial processes. The process operates at lower temperatures and pressures, accommodating heat-sensitive compounds and reducing energy consumption compared to conventional distillation methods (Drioli et al. 2015). Additionally, membrane distillation effectively rejects non-volatile solutes, which is advantageous for desalination and concentration tasks. However, this technology comes with limitations. The energy-intensive nature of membrane distillation, attributed to the heating requirement, raises operational costs. Moreover, membrane degradation over time due to harsh operating conditions can compromise system performance and necessitate maintenance. Design complexities stemming from heat management, membrane selection, and temperature polarization can further challenge implementation.

Anaerobic membrane bioreactors (AnMBRs)

Anaerobic membrane bioreactors (AnMBRs) have garnered attention as a promising technology for wastewater treatment due to their potential to combine the benefits of anaerobic digestion and membrane filtration. The research on AnMBRs for water reuse from municipal wastewater has been extensively explored in recent years. The treatment of municipal wastewater at various operating conditions has recently been the subject of multiple lab-scale systems and pilot-scale AnMBR demonstrations. This is a technique for generating renewable energy and reducing greenhouse gas emissions (Chen et al. 2019; Foglia et al. 2020). AnMBR using MF and UF membranes is compared to traditional anaerobic technology for treating low-strength wastewater to retain the anaerobic biomass (Jeon et al. 2016).

The four steps of normal anaerobic treatment are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This is the logical order of the processes involved. The synthesis of volatile fatty acids, which are short-chain components, results from hydrolysis and acidogenic phases (Khan et al. 2019). During this stage, the facultative and/or obligatory anaerobic hydrolytic bacteria break down proteins, lipids, and carbohydrates into tiny water-soluble molecules (Lei et al. 2018). Fatty acids, amino acids, and monosaccharides from the first step are produced in the second stage, which is known as acidogenesis. These substances are transformed into short-chain substances, including hydrogen,



carbon dioxide, alcohol, and aldehydes. Current bacterial consortia and environmental factors regulate the properties of acidogenic products. Acetogenesis, the third stage of the anaerobic process, is the activity that transforms volatile fatty acids, hydrogen, and alcohol into acetate. The bacterial consortia participating in this stage are *Clostridium*, *Sporomusa*, and *Acetobacterium*. Methanogenesis, the final stage of anaerobic treatment, produces methane gas. Methanogens like *Methanosaeta* and *Methanosarcina* can convert acetate into methane. Additionally, hydrogenotrophic methanogens can make methane as a result of the reaction between hydrogen and carbon dioxide, which produces methane. The availability of substrate and methane formers completely determines the pace of methane synthesis. The oscillations in methanogenesis are a result of organic load challenges with organic substrates that are either non-degradable or degradable (Hussain et al. 2015).

Membrane configurations in AnMBRs

The two major ways in which an MBR can be built are side-stream and submerged. The membrane is placed outside the bioreactor in side-stream mode while the mixed liquor is moved to the membrane unit to produce permeate. The membrane is submerged into the primary bioreactor in the AnMBR's submerged mode, on the other hand. It is easier to attain high flux in a side-stream system with consistent cleaning and effective antifouling techniques. Nevertheless, rising energy costs and ongoing cleaning could result in higher operating costs. The submerged configuration, on the other hand, just needs minimal operational requirements and little energy. Only a few thorough cleaning techniques can be used because the membrane is still inside the anaerobic tank (Shahid et al. 2020). Different AnMBR configurations have been used depending on the anaerobic treatment's scope. Some of the popular bioreactors for AnMBRs are the completely stirred tank reactor, up-flow anaerobic sludge blanket, and anaerobic fluidized bed bioreactor. AnMBR's submerged format can also be used as a two-stage system with a membrane tank that is separate from the primary bioreactor (Aslam et al. 2022). Due to its simplicity of operation and maintenance, when full-scale applications are to be considered, the two-stage arrangement may be advised for AnMBRs (Shin and Bae 2018; Song et al. 2018).

In a study by Liu et al., (Liu et al. 2020a, b); RO and anaerobic fixed-film membrane bioreactor (AnfMBR) technology integrated for the reclamation of municipal wastewater to high-grade product water (Fig. 2), whose findings indicated that the proposed process's product water might satisfy NEWater-like quality standards. Due to the fixed anaerobic biofilm being used in the reaction chamber of the AnfMBR and the low suspended solids in the mixed liquor as well as the fact that the membrane fouling in the AnfMBR

was primarily caused by the cake layer, the intensity of gas sparging for membrane scouring was significantly reduced (Liu et al. 2020a, b). According to estimates, AnMBRs use 70–100% less energy than the activated sludge process (Seib et al. 2016). To further lower AnMBR energy consumption and extend membrane run-time between cleanings, additional work in system hydraulic optimization, membrane operational methods, and membrane cleaning approaches would be beneficial.

High retention AnMBR systems have emerged, resulting from the recent progress and application of advanced wastewater treatment and reuse. These systems are two examples of anaerobic membrane distillation bioreactors (AnMDBR) and anaerobic osmotic membrane bioreactors (AnOMBR). For long-term distillation with the polyvinylidene fluoride (PVDF) membrane, the integration of MD processes with AnMBRs as AnMDBR enhanced contaminants removal for water reuse applications, TP was completely rejected, and > 98% rejection of dissolved organic carbon was also achieved (Kim et al. 2015). AnOMBR integrating the FO process with anaerobic treatment, is an advanced option for wastewater treatment. The osmotic pressure difference that forms between solutions and acts as the driving force is responsible for water's movement through the semipermeable membrane from a feed solution to a draw solution. Regenerating the draw solution allows for the use of NF and/or RO to create clean water during the AnOMBR process (Xie et al. 2015). According to the proposed design of AnOMBR, total ammonia nitrogen, total Kjeldahl nitrogen, and TP rejection rates have been as high as 96.95%, 95.87%, and 99.83%, respectively. This has led to low nutrient concentrations in the recovered water (Schneider et al. 2019).

AnMBRs offer advantages such as efficient organic matter removal, biogas production, and reduced sludge production compared to conventional aerobic systems (Zieli and Ojo 2023). The anaerobic environment in these reactors fosters the breakdown of complex organic compounds, yielding methane-rich biogas, which can be harnessed as a renewable energy source. Moreover, the incorporation of membrane filtration helps retain biomass and suspended solids, resulting in higher effluent quality and minimized post-treatment requirements (Aslam et al. 2022). However, AnMBRs are not devoid of challenges. Membrane fouling remains a major concern, often necessitating energy-intensive cleaning processes that can reduce operational efficiency and increase costs (Zieli and Ojo 2023). The anaerobic conditions also pose limitations on treating certain recalcitrant compounds, impacting the reactor's overall treatment capacity (Lim et al. 2020).

In an anaerobic hybrid system by Bilici et al., (Bilici et al. 2025), landfill leachate was treated using chemical coagulation, an electro-membrane bioreactor (e-MBR)



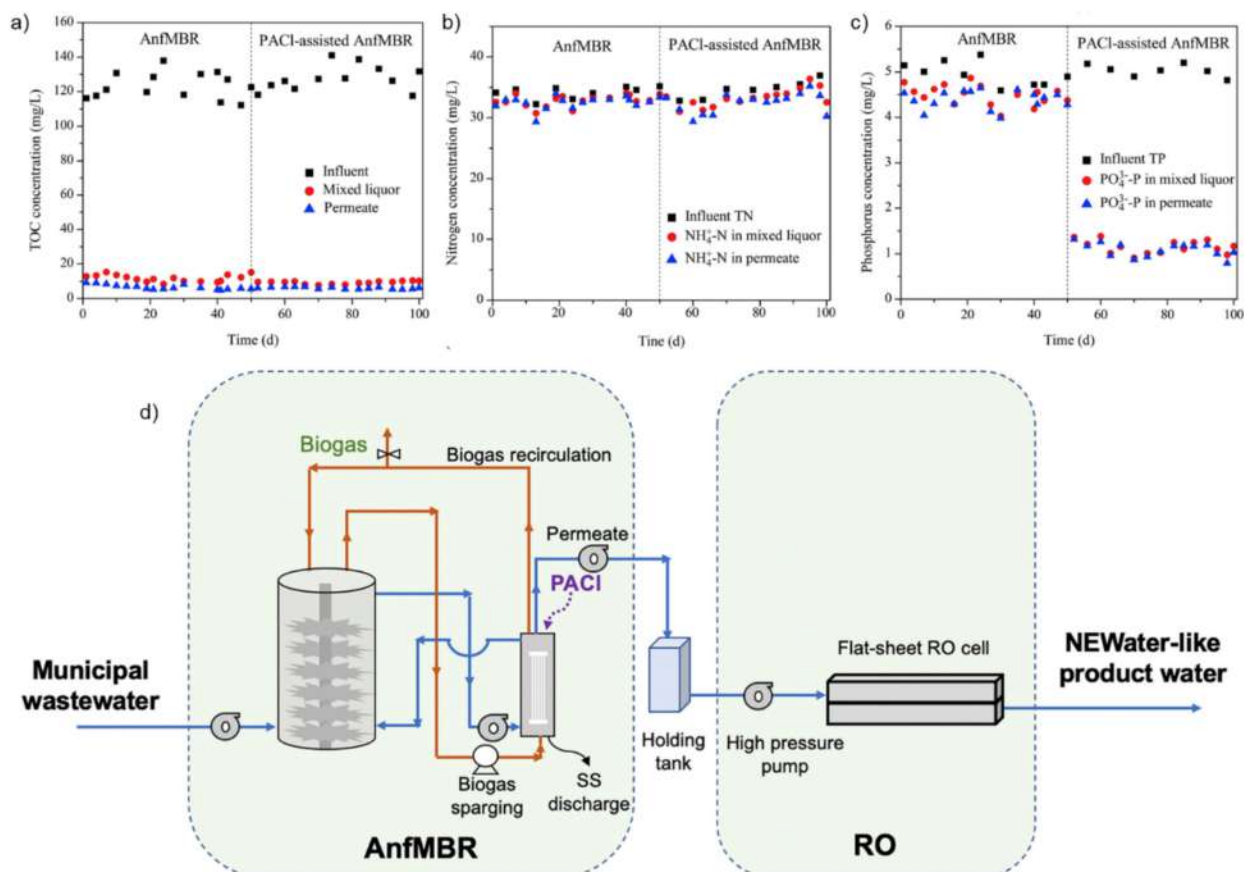


Fig. 2 (a) TOC, (b) nitrogen, and (c) phosphorus concentration profiles in AnfMBR, (d) Schematic diagram of the integrated AnfMBR-RO process; Reprinted with permission from Ref (Liu et al. 2020a, b), Copyright [2020] Elsevier B.V

with an Fe electrode and an UP150 membrane. Optimal coagulation (1.0 g L^{-1} alum, pH 9) achieved 31.16% COD removal. e-MBR (5–20 V) improved COD, TPC, and color removal (> 90%), while anaerobic treatment (10 days) reached 99.25%, 100%, and 99.57%, respectively (Bilici et al. 2025). A hollow fiber submerged AnMBR system by Saquib et al., (Saquib et al. 2024) treated RB5 diazo dye wastewater over 117 days. Phase 1 (51 days) used natural aeration, while Phase-2 (66 days) applied intermittent forced aeration. tCOD and sCOD removal improved from 88.43% to 90.82% (P-1) to 94.30% and 95.79% (P-2). Color reduction reached 83.40% in P-2. Clostridium dominated microbial communities, aiding dye degradation (Saquib et al. 2024). An MFC-AnMBR system in Huang et al., (Huang et al. 2024) treated swine wastewater ($3000\text{--}12000 \text{ mg L}^{-1}$ COD) over 185 days, enhancing organic removal, methane production, and membrane longevity. It achieved 99.0% COD removal and extended membrane life by 40+ days. The bioelectric field reduced SMP (52.7%) and EPS (15.7%) and inhibited membrane-fouling bacteria (Huang et al. 2024).

Photocatalytic membrane reactor/bioreactors

The development of photocatalytic membranes, which combine membrane filtration and organic degradation by photocatalysis in a single unit, has given a practical alternative for simultaneous water purification (Kumari et al. 2022). This novel combination not only assures water purification but also minimizes energy consumption for organic pollution treatment, which is consistent with the principles of sustainable development. Fujishima and Honda initially advanced photocatalysis in 1972, demonstrating that solar light could split water into hydrogen and oxygen over a Titanium dioxide (TiO_2) electrode (Honda 1910). Photocatalytic breakdown of organic contaminants involves a series of steps. The first step involves the adsorption of excitons and reactants. When the energy of the irradiated light meets or exceeds the semiconductor's bandgap, electrons in the semiconductor are stimulated from the valence band to the conduction band, resulting in an equal number of unoccupied sites. The last step is the breakdown of polluting molecules (Tong et al. 2012)(Fig. 3a). Photocatalytic degradation involves reactive radicals such as photo-induced holes with varying



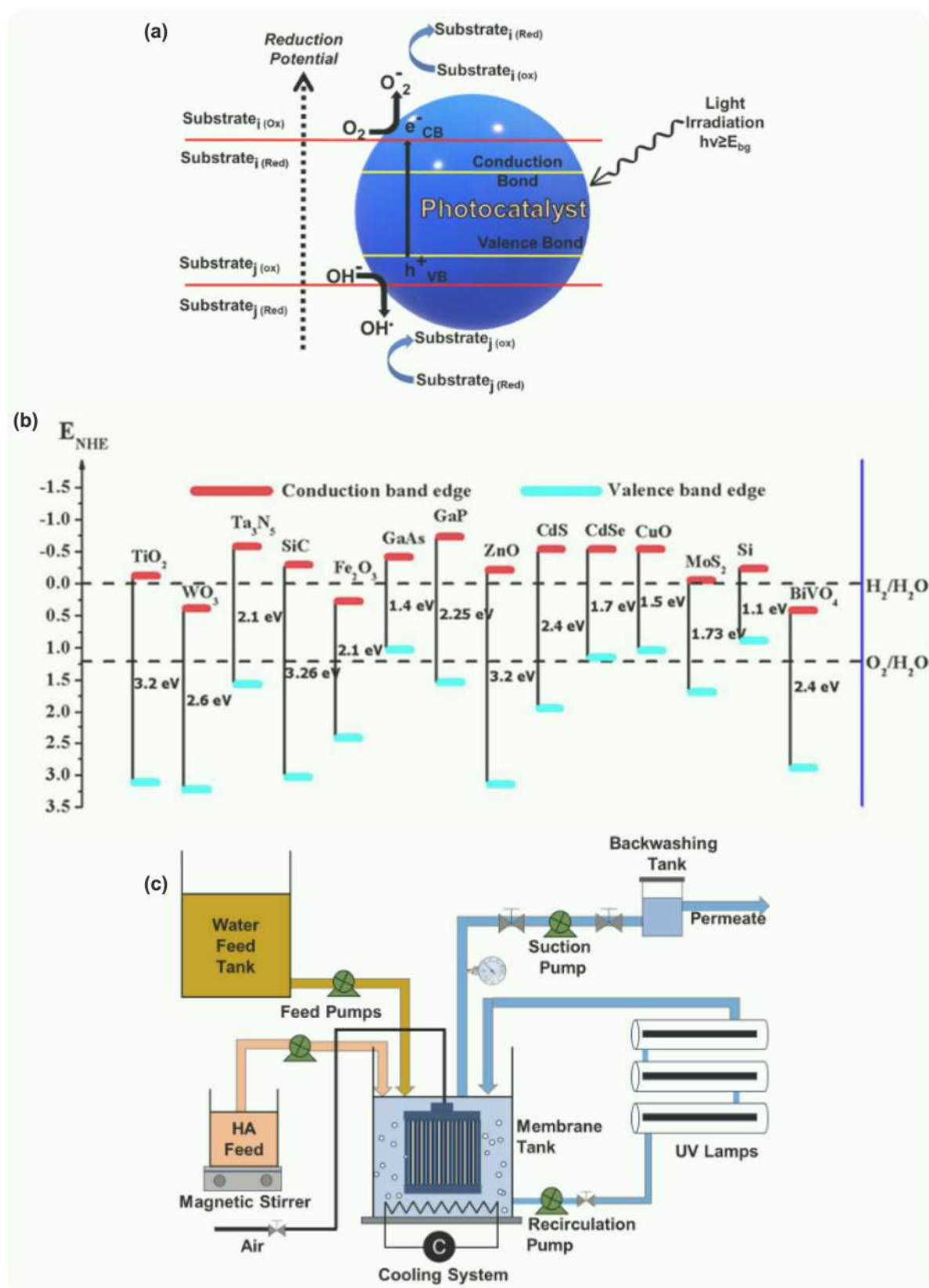


Fig. 3 (a) Photocatalytic oxidation process, (b) band structures of typical semiconductor photocatalysts (Zhang et al. 2024), (c) Schematic diagram of the hybrid photocatalysis–submerged UF membrane

system for continuous operation; Modified and reprinted with permission from Ref (Patsios et al. 2013), Copyright [2013] Elsevier B.V

oxidation abilities, superoxide anions ($O_2/O_2^{\bullet-} = -0.33$ V), and hydroxyl radicals ($OH^-/OH^\bullet = 1.99$ V). Photo-induced electrons convert oxygen to superoxide anions, while holes transform water or OH^- to $OH^\bullet$. The help of these reactive radicals and photoinduced holes promotes ring-opening and bond-breaking reactions in organic molecules, resulting in the breakdown of contaminants in wastewater into carbon dioxide.

Photocatalyst

Photocatalysis is a chain process that involves the excitation of charge carriers and their outputs for redox reactions. Therefore, the photocatalyst plays a crucial role in determining a catalytic process's light-harvesting efficiency and final throughput. The development of high-performance photocatalytic membrane technology focuses on exploiting catalysts with high quantum efficiency. TiO_2 is a metal oxide semiconductor that has been widely employed in photocatalysis for many years. It has three polymorphs: anatase, rutile, and brookite. Rutile is the most frequent natural form of TiO_2 , with metastable anatase and brookite transforming into thermostable rutile at temperatures above 600 °C. TiO_2 , the most popular semiconductor photocatalyst, has an absorption threshold of 387.5 nm, which is lower than the visible light range (390–780 nm) (Fig. 3b). Without additional modifications, TiO_2 photocatalysts can only be activated by UV light, limiting their future development. As a result, heteroatom doping, vacancy engineering, heterostructure manufacturing, and dye sensitization have been developed to improve visible light responsiveness and charge dynamics for faster photodegradation rates (Awfa et al. 2018).

Cadmium sulphide (CdS) photocatalyst is a common example of a metal sulphide that has received attention for its visible light sensitivity and high photocatalytic activity. However, the self-oxidation of S^{2-} by photo-induced holes causes CdS to become unstable throughout the photocatalysis process. Polymeric semiconductors, like carbon nitride, are gaining popularity in photocatalysis due to their metal-free properties and ability to absorb visible light. However, their quantum efficiency is currently insufficient due to limited electrical conductivity in the basal plane. Multiple ways have been developed to improve photocatalytic efficiency and stability to overcome the drawbacks of different semiconductors to overcome the drawbacks of different semiconductors (Ashley et al. 2021). These include controlling crystalline size at the nanometer scale, adjusting the valence band and conduction band positions by doping with anions or cations, and narrowing the bandgap (Liu et al. 2016); depositing noble metals such as Pt and Ag; doping with non-metal elements (B, C, N, F, S, P, and I) or metal elements (Fe, Zn, Cu, Ni, Mn, V, and Co) to allow visible light absorption and limit interfacial charge carrier recombination; and

creating heterojunctions between two or more semiconductors to increase charge separation and widen the wavelength response range (Khaki et al. 2017). These methodologies have been effectively used to modify photocatalysts, resulting in reasonably high pollutant removal efficiency. Other semiconductor materials discovered and exploited in photocatalysis include WO_3 , Ta_3N_5 , SiC, Fe_2O_3 , GaAs, ZnO, CdSe, CuO, and $BiVO_4$ (Hadjnadjev-Kostic et al. 2017).

Photocatalysis coupling with membrane

The combination of photocatalysis and membranes creates a synergistic effect, utilizing both technologies' strengths. Photocatalysis can effectively degrade and mineralize organic contaminants, including recalcitrant and toxic compounds. Photocatalytic activity on the membrane surface can prevent fouling by degrading foulants, organic matter, or microbial biofilms, extending membrane lifespan and reducing the need for maintenance. Photocatalysis uses solar energy as a driving factor, which reduces dependency on non-renewable energy sources. Furthermore, the photocatalytic degradation process can convert organic contaminants into harmless byproducts, resulting in a more environmentally friendly treatment strategy in a single unit.

Photocatalytic membrane reactors using suspended photocatalysts

Suspended photocatalytic membrane reactors (PMRs) are a unique arrangement in which the membrane module is physically isolated from the photocatalysis reactor. This membrane unit can be one of two types: fully immersed within the photocatalysis unit or separated from the photocatalysis unit. In this configuration, the membrane's major function is to act as a barrier, effectively separating the catalysts from the products and byproducts produced during photocatalytic oxidation. This separation makes collecting and reusing catalysts easier, increasing the system's overall efficiency. In general, PMRs with suspended photocatalysts are more successful at treating pollutants because they have a much larger active surface area available during the treatment process, and changing the catalyst load in suspended PMRs is a simpler procedure. However, in suspended PMRs, photocatalyst recovery is less efficient than in immobilized PMRs, where photocatalysts are incorporated directly onto or into the membrane. Furthermore, suspended photocatalysts may restrict the amount of light available for the photocatalytic process, and collisions between photocatalysts on the membrane surface, especially in immersed-type suspended PMRs, might cause membrane degradation.

Several suspended PMRs have been developed and are commonly utilized in wastewater treatment. For example, (Li et al. 2018) studied the degradation of amoxicillin in a



submerged ceramic membrane photocatalytic reactor. They used a TiO_2 photocatalyst and a Ceraflo CF-3604-DH hollow plate ceramic membrane in the SCMPR. The ceramic membrane (with pore size smaller than 500 nm) effectively separated TiO_2 catalysts (average size of 1.4 μm). Although membrane fouling was detected during the operation, it was successfully cleared by backwashing. The effect of TiO_2 loading was also investigated, and it was discovered that high TiO_2 could cause a decrease in degrading performance due to light-blocking and scattering effects (Li et al. 2018).

Patsios et al., (Patsios et al. 2012); also demonstrated a synergistic impact of photocatalysis and UF membranes in the treatment of humic acid (Fig. 3c). In their experiment, a PVDF-UF membrane with a pore size of 40 nm was immersed in a photocatalytic reactor containing Degussa P25 TiO_2 particles (average particle size of 21 nm). The ideal pH for HA mineralization was discovered to be 5.5, with HA mineralization rates of 73.9 and 62.6% at starting HA concentrations of 5.0 and 10.0 mg L^{-1} , respectively. To prevent membrane fouling during continuous usage, periodic backwashing was employed. Comparative tests revealed that a relatively low backwashing frequency of 1/15 (1 min backwashing after 15 min of filtration) resulted in greater HA removal and filtration efficacy than the 1/9 backwashing strategy (Patsios et al. 2013). Additionally, Laohaprapanon et al., (Laohaprapanon et al. 2015); used ZnO in a dead-end slurry PMR system with a PVDF membrane to degrade reactive black 5 (RB5). The study indicated that ZnO outperformed TiO_2 for RB5 degradation in batch reactors and PMR (Laohaprapanon et al. 2015). Table 1 summarises research on split-type PMRs (PMRs with suspended photocatalysts).

Photocatalytic membrane reactors using immobilized photocatalysts

Two approaches to developing photocatalytic membranes exist: coating a monolayer or multilayer of photocatalyst onto the membrane surface and combining photocatalysts with membrane components during membrane fabrication. Photocatalysts can be used with or coated on polymers such as PVDF (Paredes et al. 2018), CA (Wei et al. 2019), PEI (Zhang et al. 2018a, b), PES (Salim et al. 2017), and PSF (Kuvarega et al. 2017). PMRs with immobilized photocatalytic membranes are influenced by variables such as membrane applying type (coating or blending), light source (UV or visible lights), photocatalyst characteristics, membrane permeability, pollutant concentration, membrane substrate materials (polymer or ceramic), PMR design (dead-end mode or crossflow mode), and photocatalyst dopant amount (Wei et al. 2019).

A visible-light photocatalytic MBR (R3) with a $\text{g-C}_3\text{N}_4$ modified membrane was developed for fouling control and effluent improvement, compared to R1 (ceramic membrane) and R2 ($\text{g-C}_3\text{N}_4$ membrane in dark). Over 60 days, R3 achieved superior COD (22.0 mg L^{-1}) and NH_4^+N (1.02 mg L^{-1}) removal, with a thinner cake layer (2.46 μm vs. 3.52 μm in R1, 4.97 μm in R2). Visible light enhanced *Bacteroidetes* and *Chryseolinea* abundance, improving microbial metabolism and electron transfer (Qi et al. 2025). This study demonstrated photocatalysis as an eco-friendly strategy for bacteria inactivation and antifouling in MBRs using solar energy (Qi et al. 2025). Ghosh et al., (Ghosh et al. 2023) investigated ciprofloxacin (CPX) removal and *E. coli* inactivation using a photocatalytic reactor (PCR) with 0.5 g L^{-1} Ag-doped TiO_2 (bandgap: 2.41 eV) under

Table 1 Studies into the photodegradation of various aqueous contaminants by PMRs (Suspension type) (Zhang et al. 2024)

Photocatalyst	Membrane	Pollutants	Process characteristic	References
TiO_2 P25	Hollow plate ceramic	Amoxicillin (AMX)	80% AMX removal at pH=6.5, $[\text{TiO}_2]_0 = 400 \text{ mg L}^{-1}$	(Li et al. 2018)
TiO_2 P25	PVDF UF	Humic acids (HAs)	74% HA removal at pH=5.5, $[\text{TiO}_2]_0 = 0.75 \text{ g L}^{-1}$	(Patsios et al. 2013)
TiO_2 P25	Tubular asymmetric TiO_2	Humic acids (HAs)	78% TOC removal at pH=3, $[\text{TiO}_2]_0 = 1.5 \text{ g L}^{-1}$	(Szymański et al. 2016)
TiO_2 P25	Flat sheet PES	Humic acids (HAs)	70% TOC removal at pH=6.5, $[\text{TiO}_2]_0 = 0.5 \text{ g L}^{-1}$	(Darowna et al. 2017)
TiO_2 P25 and nano-structured TiO_2 /silica	PVDF hollow fiber MF	Fulvic acids (FAs)	Nearly 70% TOC removal at pH=6.5, airflow = $0.06 \text{ m}^{-3} \text{ h}^{-1}$	(Fu et al. 2006)
TiO_2 P25	PVDF MF	Bisphenol-A (BPA)	97% BPA degradation at pH=4, $[\text{TiO}_2]_0 = 0.5 \text{ g L}^{-1}$	(Chin et al. 2007)
ZnO and TiO_2	PVDF MF	Reactive black 5 (RB5)	95% colour removal at pH=7, $[\text{ZnO}]_0 = 1.25 \text{ g L}^{-1}$	(Laohaprapanon et al. 2015)
Nano- TiO_2	PVDF and PAN	Acid red B (ARB)	82.32 dyes rejection and at pH=6, $[\text{TiO}_2]_0 = 1.5 \text{ g L}^{-1}$	(Jiang et al. 2010)



blue LED (180 min) and a submerged MBR (2.75 days HRT, 30 day SRT, 0.68 bar TMP). The MBR-PCR system achieved ~99% COD, nitrogen, and CPX removal with complete disinfection of 10^6 CFU mL⁻¹ *E. coli*. CPX biodegradation was predominant in MBR, while h^+ radicals drove photocatalysis. The absence of an *E. coli* inhibition zone confirmed CPX detoxification, highlighting the hybrid process as a promising solution for pharmaceutical removal and wastewater disinfection (Ghosh et al. 2023).

In a study, Huang et al., (Huang et al. 2019) developed a PVDF-supported g-C₃N₄ (GCN) photocatalytic membrane via vacuum filtration. A certain volume of g-C₃N₄ solution was applied to a PVDF disc membrane, followed by the permeation of polyethylene glycol (PVG) and glutaraldehyde (GA) as cross-linkers. As GCN loading increased, membrane pore size and permeation flux dropped. Atomic force microscopy (AFM) scanning revealed that the roughness of the membrane surface increased with GCN loading. The photocatalytic activity was assessed by treating rhodamine B (RhB) and tetracycline (TC) with visible light. The M3 membrane, with a 7 mg GCN loading, has the highest photocatalytic activity for RhB (84.24%) and TC (71.26%) degradation (Huang et al. 2019). Liu et al., (Liu et al. 2020a, b); also created a dynamic photocatalytic membrane from zinc indium sulfide (ZnIn₂S₄) and PVDF using dead-end filtration deposition. The dynamic ZnIn₂S₄@PVDF photocatalytic membranes demonstrated remarkable degradation capability. The M3 membrane (ZnIn₂S₄@PVDF, 2.6 mg cm⁻² catalyst loading) removed 97.2% of fluvastatin and 53.3% of total organic carbon (TOC). After 6 passes on the M3 membrane, the ZnIn₂S₄@PVDF photocatalytic membrane maintained a fluvastatin degradation efficiency of 91.5% (Liu et al. 2020a, b).

Yu et al., (Yu et al. 2018); created a photocatalytic membrane by combining mesoporous graphitic carbon nitride/titanium dioxide (mpg-C₃N₄/TiO₂) nanocomposites with a polysulfone (PSf) matrix. The insertion of mpg-C₃N₄/TiO₂ particles reduced the MWCO and membrane permeability. Furthermore, the addition of mpg-C₃N₄/TiO₂ or TiO₂ strengthened the membrane matrix. The PSf-3 membrane, including 1% mpg-C₃N₄/TiO₂, showed high hydrophilicity (contact angles of 70.8°, 67.7°, 65.6°, and 58.1°, respectively). Furthermore, the PSf-3 membrane showed the best degradation performance for sulfamethazine, with a degradation rate of 69% in a 3 h run under solar light irradiation (Yu et al. 2018). Table 2 summarises recent studies on immobilized PMRs used to degrade organic contaminants.

Electrochemical processes coupled with membrane reactors/bioreactors

The electrochemical membrane reactor is a membrane process coupled with an electrochemical process used for

water and wastewater treatment. Without altering the microbiological activity inside the reactor or the effectiveness of pollutant breakdown, an electric field with periodic contact can also increase the hydraulic efficiency of the membrane system (Giwa et al. 2019). In an electrochemical cell with a catalyst coating, conductive membranes serve as the cathode and the anode, speeding up the rate of pollutant destruction. The coagulants used in the electro-coagulation procedure are created on-site by electrically dissolving iron or aluminum ions from the metal electrodes. In this process, metal ions are created at the anode, and hydrogen gas is created at the cathode. The emitted hydrogen gas keeps the flocculated particles floating on the surface. These systems can improve pollutant removal/degradation and also prevent membrane fouling by employing electrocoagulation mechanisms or direct oxidation processes (Hosseinizadeh et al. 2015). Additionally, regular membrane cleaning for a system like this, following the application of an electric field, would not be required due to the decline in MBR fouling, therefore lowering maintenance costs. These electrochemical MBRs have effectively removed pollutants and reduced membrane fouling, and they may be used for municipal and industrial wastewater.

In a hybrid system where the electrochemical reactor is placed at the pre-treatment stage, the raw wastewater will first be treated using a method like electrocoagulation before being subjected to membrane filtration and biodegradation. On the other hand, a post-treatment procedure may involve additional processing of the membrane bioreactor's effluent. An electrochemical reactor's pre- and post-treatment demonstrates the increased overall elimination of recalcitrant compounds, including pharmaceuticals, pesticides, personal care products, micropollutants, etc. (Gurung et al. 2018). Another approach involves placing the electrodes inside the MBR to reduce overall space footprints while providing effective removal of pollutants and micropollutants in a single process.

Hosseinizadeh et al., (Hosseinizadeh et al. 2015); introduced a new hybrid electro-membrane bioreactor (HEMBR) for RO pre-treatment and advanced treatment of effluent by integrating electrical coagulation with an MBR (Fig. 4a) and further compared it with a conventional MBR. Results and their statistical analysis showed that the removal efficiency for suspended solids (SS) was almost 100% for both reactors. HEMBR removal of COD improved by 4% and membrane fouling was alleviated according to TMP. The TMP value gradually grew from 3 to 7 kPa after 6.5 days of operation, and then rapidly increased to 60 kPa at the end of the first cycle (11.5 days). TMP values for HEMBR are significantly lower than TMP values for MBR, showing that electrical coagulation improves membrane function. In other words, electrical coagulation minimizes membrane fouling and allows for a longer duration of operation before membrane



Table 2 Studies into the photodegradation of various aqueous contaminants by PMRs (Immobilized type)

Photocatalyst	Membrane	Irradiation	Pollutants	Process characteristic	References
Titanate nanotube	PVDF hollow fiber	UV-A	Aerobically treated palm oil mill effluent	78.2% removal at 240 min	(Subramaniam et al. 2017)
TiO ₂ P-25	PVDF hollow fiber	UV-C	CBZ, DCF, IOP, GEM, MET, SMX, TMP, WAR	completely degraded within 1 h	(Paredes et al. 2018)
g-C ₃ N ₄ nanotube/RGO	Disc CA	Visible	RhB	96.1% RhB removal	(Wei et al. 2019)
C ₃ N ₄	Disc PVDF MF	UV-C	RhB, TC	84.24% RhB and 71.26% TC degradation in 4 h	(Huang et al. 2019)
TiO ₂ -P25	PEI hollow fiber	UV-A	AO7	68% AO7 removal in 75 min	(Zhang et al. 2018a, b)
GO/CN/ TiO ₂ -CNT	Al ₂ O ₃	UV	RhB	More than 60% RhB removal in 180 min	(Zhang et al. 2017)
mpg-C ₃ N ₄ / TiO ₂	PSF	Solar light	SMX	69% SMZ degradation in 30 h	(Yu et al. 2018)
Nitrogen-doped graphene/ TiO ₂	PSF	UV/sunlight	MB	80.6% and 77.5% MB removal within 120 min	(Xu et al. 2017)
TiO ₂ and Cu ₂ O nanowires	rGO	UV	MO	Over 90% MO degradation in 120 min	(Wang et al. 2018)
g- C ₃ N ₄	Flat sheet PES	UV-B (312 nm) and visible	PHN	43.3% PHN removal in 300 min	(Salim et al. 2017)
Ag doped GO/ Titanate NTs	Cellulose filter	Visible	MB	More than 90% MB removal	(Liu et al. 2018)
N, Pd Co-doped TiO ₂	PSF	Visible	EY	97% EY removal in 4 h	(Kuvarega et al. 2017)
g- C ₃ N ₄ /CNTs	Al ₂ O ₃	Visible	PHN	94% PHN removal after 60 min	(Wang et al. 2017)
GO/TEOA-TNWs	Disc cellulose	UV	CR	93.1% CR degradation within 150 min	(Liu et al. 2017)
TiO ₂ /ZnO	PVDF flat sheet	Visible	MB	More than 80% MB degradation within 30 min	(Yan et al. 2017)
g-C ₃ N ₄ NS/RGO	CA	Visible	RhB	60% of RhB removed in 90 min	(Zhao et al. 2016)
N-doped TiO ₂	Al ₂ O ₃	UBA/UVB/ visible	CBZ	55% CBZ removal in 120 min at 45 °C	(Horovitz et al. 2016)
TiO ₂ /Carbon	Al ₂ O ₃	UV	RhB	60% TOC removal in 120 min	(Wang et al. 2015)
TiO ₂ /rGO	Al ₂ O ₃	UVA/Visible	MO/MB	65% MO and 63% MB removal	(Athanasakou et al. 2015)
TiO ₂	PVDF	UVA	MB-SDS	99% MB-SDS rejection at 0.5 bar	(Ngang et al. 2012)
TiO ₂	PVDF	UV/visible	RB5 dye, E. Coli	Complete RB5 removal in 1 h; Complete E. Coli removal in 1 min	(Damodar et al. 2009)
ZnIn ₂ S ₄	PVDF	UV/visible	Fluvastatin	97.19% fluvastatin and 53.29% TOC removed	(Liu et al. 2020a, b)
rGO	TiO ₂	UV/visible	Propranolol (PR)	100% PR removal in 60 min	(Gao et al. 2020)
TiO ₂	Anodized aluminium oxide (AAO)	UV	MB	80% MB removal	(Berger et al. 2020)

regeneration, lowering membrane washing expenses. An electrochemical technique combined with MBR has been shown to remove 75–90% of resistant micropollutants such as diclofenac, carbamazepine, and sulfamethoxazole as shown in Fig. 4b (Asif et al. 2020).

A pilot-scale electrochemical MBR was designed by Hasan et al., (Hasan et al. 2014); to investigate the influence of pollutant loading rate and process variables on membrane

fouling propensity after examining the pattern in nutrient removal efficiency. Results demonstrated that under steady-state circumstances, this hybrid system removed 90% of organic matter and 99% of nutrients, including phosphate and ammonia. Additionally, this hybrid membrane system's TMP did not considerably rise, and its stated fouling rate was 0.02 kPa day⁻¹ (Hasan et al. 2014). The hybrid arrangement, in which the electrodes are placed externally into a



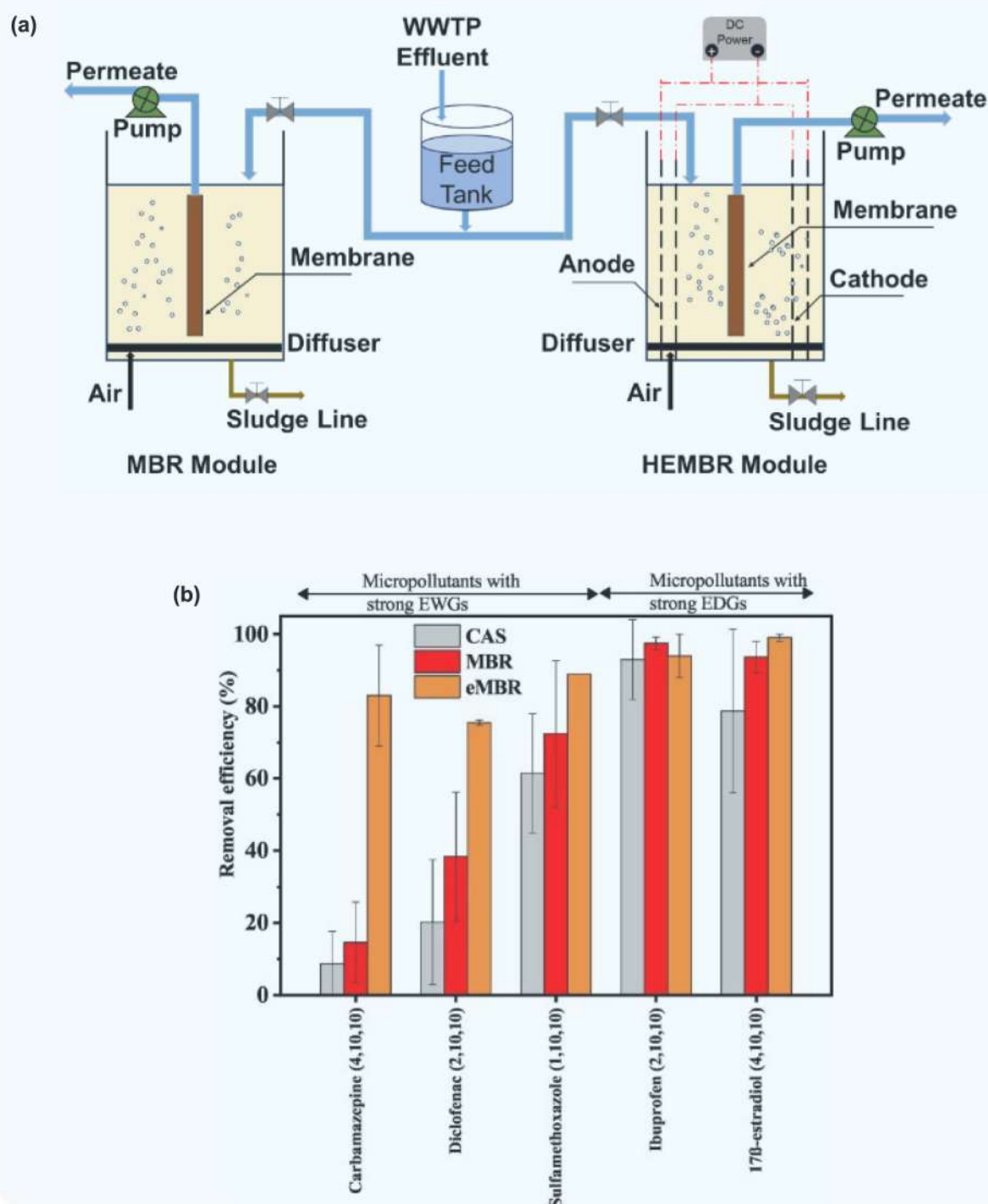


Fig. 4 (a) Schematic of the experimental setup of MBR and HEMBR pilot plant (Hosseinzadeh et al. 2015), (b) Removal of micropollutants by different treatment processes including eMBR, MBR, and

conventional activated sludge (CAS); reprinted with permission from Ref (Asif et al. 2020), Copyright [2020] Elsevier B.V.

separate electrochemical reactor, has been examined for the treatment of contaminants from municipal, industrial wastewater, and landfill leachate and has produced effective results (Bani-Melhem and Smith 2012; Gurung et al. 2018;

Ukundimana et al. 2018). Gurung et al., (Gurung et al. 2018) investigated the electrochemical oxidation (EO) of antibiotic carbamazepine (CBZ) and MBR effluent using Ti/Ta₂O₅-SnO₂ electrodes (Fig. 5a). After 8 h of electrolysis under a



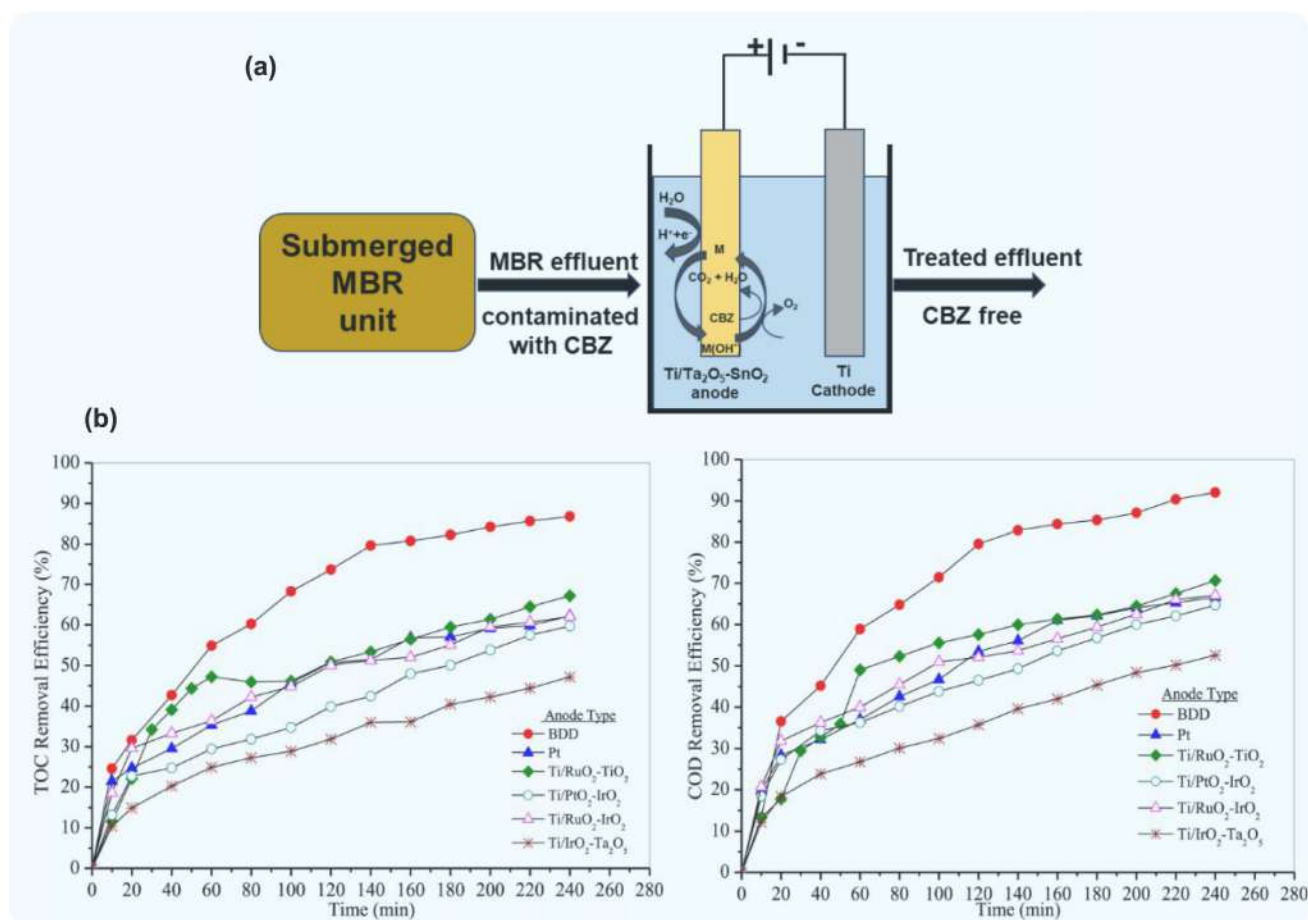


Fig. 5 (a) Schematics of hybrid electrochemical membrane bioreactor setup reprinted with permission from Ref (Gurung et al. 2018), Copyright [2018] Elsevier B.V., (b) COD and TOC removal from UF

effluent with different DSA anodes ($j=360 \text{ A m}^{-2}$); reprinted with permission from Ref (Ukundimana et al. 2018), Copyright [2018] Elsevier B.V

current density of 9 mA cm^{-2} , pH 6, temperature of 30°C , and $0.1 \text{ M Na}_2\text{SO}_4$ electrolyte, the optimum removal of CBZ (20 mg L^{-1}) and TOC was 75.5% and 71.1%, respectively (Gurung et al. 2018).

Keerthi et al., (2013); examined three different fusions of modes: MF and electrocoagulation combined, MBR, and electrocoagulation integrated with MBR. Out of these three, electro-coagulation combined with an MBR performed the best in lowering fouling and removing COD and metal from tannery effluent (Keerthi et al. 2013). Also, the study by Vijayakumar et al., (Vijayakumar et al. 2015) claims that, compared to traditional MBR, electro-coagulation using aluminum as the anode and stainless steel as the cathode is very effective at removing metal (Vijayakumar et al. 2015). Laera et al., (Laera et al. 2011) stated in their study that with an initial concentration of 25 mg L^{-1} , the integrated MBR was effective in removing Cr, Cu, and Zn, with an average removal efficiency of more than 90%. Additionally, this technique enhanced permeation flux and extended membrane life. The treatment of wastewater from tanneries,

pharmaceutical manufacturing facilities, and colored wastewater from the textile industry that is intended for zero discharge is suited for this type of combined MBR. However, further analysis is required to assess the excess sludge production, costs, and parameter optimization for SRT and HRT (Laera et al. 2011).

Investigations on electrochemical membrane bioreactors (eMBR) have found that these devices are highly effective at removing organic materials, nutrients, and heavy metal ions. The removal efficiency of 92% COD, 99% $\text{PO}_4^{3-}\text{-P}$, and 99% $\text{NH}_4^+\text{-N}$, respectively, has been attained in a pilot-scale submerged membrane electro-bioreactor system used to treat municipal wastewater (Hasan et al. 2014). Borea et al., (Borea et al. 2017) suggested that sludge hydrophobicity in eMBR may be increased to around 72% by electrochemical methods, enhancing sludge dewaterability and lowering the need for membrane cleaning (Borea et al. 2017). Giwa et al., (Giwa et al. 2016); obtained high removal efficiencies of 98%, 99%, and 98%, for COD, $\text{PO}_4^{3-}\text{-P}$, and $\text{NH}_4^+\text{-N}$, respectively,

from medium-strength municipal wastewater with eMBR (Giwa et al. 2016). Ensano et al., (Ensano et al. 2016) achieved enhanced removal of diclofenac, carbamazepine, and amoxicillin of 75.25%, 73.84%, and 72.12%, respectively, because of the bioreactor's many electrochemical mechanisms (Ensano et al. 2016).

Giwa et al., (Giwa et al. 2015) developed a configuration in a computational model of an eMBR with electrodes constructed in a novel anode–cathode-membrane-module-cathode–anode to estimate the quality of the treated wastewater. COD, TP, TN, Ni, Fe, and Cr had high removal rates of 99%, 99%, 91%, 80%, 89%, and 80%, respectively (Giwa et al. 2015). To reduce membrane fouling using eMBR, the average fouling rate was lowered significantly by 7.8 times, necessitating no chemical cleaning throughout the eMBR operation (Hua et al. 2015). Ukundimana et al., (Ukundimana et al. 2018) studied UF effluent from a leachate treatment plant treated by the EO process using different dimensionally stable electrodes as Ti/PtO₂–IrO₂, Ti/RuO₂–TiO₂, Ti/RuO₂–IrO₂, and Ti/IrO₂–Ta₂O₅, boron-doped diamond, and Pt as anode and stainless-steel electrode as a cathode. The untreated UF effluent had TOC and COD values of 398.6 mg L^{−1} and 888 mg L^{−1}, respectively. Overall, the boron-doped diamond anode outperformed the other anodes under the tested conditions with removal efficiencies of 64.9–86.8% and 68.2–92.0% for TOC and COD, respectively (Fig. 5(b)) (Ukundimana et al. 2018). In general, improvements in membrane performance afforded by eMBR have led to higher permeate productivity and fewer membrane backwashing.

Belli et al., (Belli et al. 2024) evaluated azo dye removal in a UASB reactor combined with an eMBR. Using 20 A m^{−2} current density and a 6 min ON, 30 min OFF cycle, the UASB removed 57% of Drimaren Red CL-7B, while electrocoagulation in eMBR improved dye removal from 60.5% to 67.1%. The system achieved > 97% COD and NH₄⁺-N removal, with phosphate removal enhanced by electrocoagulation. Membrane fouling was reduced by 68% (0.25–0.08 kPa day^{−1}), demonstrating efficient textile wastewater treatment with enhanced pollutant removal and reduced fouling. A novel gravity-driven electro-dynamic MBR (EDMBR) using stainless-steel mesh as the anodic membrane and graphite plates as cathodes was developed for domestic wastewater treatment. Compared to a control DMBR, electrostatic adsorption shortened dynamic membrane (DM) formation to < 4 min. Electro-oxidation and biodegradation (*Pseudomonas*, *Acinetobacter*, *Exiguobacterium*) maintained a thin DM layer, enhancing flux and reducing fouling at 1.2–1.6 V. Electro-coagulation improved phosphorus removal (74–87%). EDMBR had higher permeability and lower energy consumption (0.41–0.44 kWh m^{−3}) than DMBR (0.50 kWh m^{−3}), demonstrating improved efficiency and sustainability (Hu et al. 2024).

Mao et al., (Mao et al. 2024) explores the effects of operational parameters (voltage, electrode spacing, power-on mode, and hydraulic retention time) on membrane fouling and pollutant removal in a PVDF-based eMBR. Under optimal conditions, the EMBR extended runtime by 23.4% compared to a conventional MBR, effectively mitigating fouling. Effluent quality improved, with increased removal efficiencies for chemical oxygen demand (2.25%), ammonia nitrogen (2.64%), total phosphorus (9.02%), and total nitrogen (12.1%). These findings demonstrate that applying a weak electric field enhances fouling control and pollutant removal, making EMBR a promising, sustainable wastewater treatment technology (Mao et al. 2024). Song et al., (Song et al. 2023) developed an integrated electrochemical pre-treatment and carrier-based membrane bioreactor (MBR for treating fresh leachate from waste transfer stations with high organic and NH₄⁺-N content. With a hydraulic retention time of 40 h, removal efficiencies for COD, NH₄⁺-N, SS, and TP reached 98.5%, 91.2%, 98.3%, and 98.4%, respectively, with an organic removal rate of 18.7 kg m^{−3}. Pre-treatment removed ~ 70% of refractory organics and nearly all SS, transforming humic-like acids into biodegradable compounds. The oxic MBR enhanced biomass attachment and denitrification enzyme activity, reducing membrane fouling (Song et al. 2023).

Advanced oxidation and reduction process coupled with membrane reactors

Combined treatment techniques, such as membrane separation coupled with advanced oxidation processes (AOPs), are the technology for absolute elimination or conversion into less toxic compounds of well-known pollutants such as textile dyes, pharmaceutical compounds, pesticides, personal care products, micropollutants, etc., because each method advances the benefits and gets around the drawbacks of the others. AOPs refer to a set of physical (sonolysis, cavitation), chemical (ozonation, peroxonation, Fenton), photocatalytic (UV/Solar/semi-conductors, UV/H₂O₂, UV/O₃, etc.), photochemical, and electrochemical processes (electrooxidation, electro-Fenton, etc.) that can generate strong oxidants, mainly free radicals of hydroxyl, as a strong oxidant to remove compounds that are not easily removed using conventional membrane technologies (Titchou et al. 2021).

As reactive species, hydroxyl radicals (OH•) can act unselectively on target organic compounds up to their complete mineralization in H₂O, CO₂, and inorganic ions (Sennaoui et al. 2018). Due to the non-selective nature of its reaction with the contaminants present, this free radical has a 2.05 times greater oxidizing capacity than chlorine (Rostam and Taghizadeh 2020). Typically, hydroxyl radical is produced through the combination of UV radiation, O₃, TiO₂, H₂O₂, ultrasonic wave, and electron beam irradiation. The fact that



the AOPs are implemented in mild environments like room temperature and ambient pressure is another benefit of using them. Application of AOPs has been observed in water treatment, wastewater treatment, and soil remediation (Paździar et al. 2019; Zhou et al. 2019). Integrated/hybrid reactors and bioreactors that induce AOPs with suitable and diverse membranes appear to be of great benefit under the need for an efficient treatment technology as they have higher treated water efficiencies, very low chemical expenditures, and lower energy costs, as well as improved membrane flux in addition to fouling reduction (Iglesias et al. 2016).

Membrane filtration can be integrated with AOPs as a pre-treatment stage, post-treatment stage, or one pot/hybrid process. Humic acids and all other micro-pollutants that foul or obstruct the membrane surface and pores are among the organic materials typically targeted for the pre-treatment stages to break down to reduce membrane fouling by oxidizing (Real et al. 2012). Practically, ozonation and photolysis with or without H_2O_2 are the only AOPs used as pre-treatment stages in membrane filtration (Ganiyu et al. 2015). It is common practice to use post-treatment stages in mineralizing non-rejected micropollutants in the permeate stream and highly concentrated organics in the concentrate stream. The most recent breakthrough in this area is the combined filtration and degradation of organic contaminants in a single process for hybrid processes. It is composed of self-cleaning membranes or suspended catalysts and photocatalysts, such as TiO_2 or Fenton's reagents (Fe^{2+} and H_2O_2), that can produce an $OH^\bullet$ by an electrochemical or photochemical process for oxidation (Ahmad et al. 2017). Above named AOPs, integrated with membrane reactors and MBRs, are described and examined by case study, and several other cases are also introduced in Table 3 below.

AOPs that have been combined with MRs and MBRs are more effective and complex. Jia et al., (Jia et al. 2015a) created a membrane bioreactor with three-dimensional catalytic electro-Fenton (3DCEF-MBR) for the enhanced treatment of biologically pre-treated effluent from coal gasification. According to the data, this hybrid system has high removal efficiencies for both COD and total organic carbon, with maximum removal efficiencies of 80% and 75%, respectively. After 30 days of operation, the combined system provided TMP 35% lower than standard MBR. The processes behind the performance of the 3DCEF-MBR were increased $OH^\bullet$ oxidation and bacterial self-repair. Because of this, it was anticipated that the integrated 3DCEF-MBR would be a potential technique for enhanced treatment in engineering applications (Jia et al. 2015b). Le et al., (Huong Le et al. 2019) developed a mixed metal-loaded graphene hollow fiber over a membrane reactor until effective electro-Fenton purification as a hybrid oxidation/membrane process to treat paracetamol effluent. The current efficiency value of the mineralization was significantly enhanced by 165%

Table 3 AOP integrated with Membrane Reactor/MBR systems for different wastewater treatment

AOP type	Membrane reactor or MBR	Wastewater	Comment	References
Fenton oxidation	Membrane reactor	Dye, Antibiotic-related micro-contaminants, Synthetic	Effluent met urban recycling water quality standards	(Feng et al. 2010; He and Wei 2010; Karaolia et al. 2017)
Ozonation	MBR	Textile, Pharmaceutical Municipal, Hospital, Pharmaceutical, Synthetic	Wastewater reclamation and water recovery Enhanced removal efficiencies between 36 and 67%	(Aydiner et al. 2019; Lan et al. 2020) (Gommers et al. 2007; Mascolo et al. 2010; Vo et al. 2019; Wang et al. 2008; Zhang et al. 2018a, b)
Ozonation	Membrane reactor	Recalcitrant organic, Organic endocrine-disrupting pollutants	Recalcitrant organic compounds removed	(Chan et al. 2012; Ho et al. 2012)
Electro-chemical	MBR	Leachate landfill, Municipal, Hospital, Synthetic	Enhanced effluent quality and anti-fouling ability	(Aloui et al. 2009; Chung et al. 2016; Ouarda et al. 2018; Yang et al. 2019)
Electro-chemical	Membrane reactor	Dye, Oily, and Phenol	Enhanced antifouling ability for industrial wastewater treatment	(Yang et al. 2018, 2011)
Photocatalytic	MBR	Industrial textile, Pharmaceutical, Petroleum refinery, Pesticides	30–40% reduction of fouling and leading to industrial water reuse	(Casas López et al. 2010; Gurung et al. 2019; Oliveira et al. 2020)
Photocatalytic	Membrane reactor	Industrial textile, Pharmaceutical, Petroleum refinery, Pesticides, Congo red dye, Acid red B	Enhanced removal up to 54% for hybrid system	(Ashar et al. 2020; Desa et al. 2019; Deveci et al. 2016; Hairom et al. 2014; Janssens et al. 2017; Jiang et al. 2010; Kertész et al. 2014)

and stayed stable for three consecutive cycles by combining filtration and electrochemical procedures. By using this method, it is possible to create low-cost catalytic membrane reactors that have the potential to mineralize recalcitrant compounds and have high flux and selectivity from the materials' reactivity as compared to sieving (Huong Le et al. 2019). Another study performed by Nivya and Minimol Pieus, (Nivya and Minimol Pieus 2016) who built a photo-electro-Fenton-MBR system for landfill leachate treatment as a vital component of municipal solid waste management, demonstrated enhanced pollutant removal efficiency by implementing combination treatment, which involved the photo-electro-Fenton process followed by the MBR (Nivya and Minimol Pieus 2016).

Laera et al., (Laera et al. 2011) planned and created a UV-H₂O₂-MBR system for treating municipal and industrial wastewater. They contrasted a system of chemical oxidation in MBR with a standard configuration in their design, and the outcomes revealed COD removal rates of about 85–95% (Laera et al. 2011). In another study by Moser et al., (Moser et al. 2018); using a UV-H₂O₂-MBR system as an NF pretreatment for the petroleum refinery whose schematics are shown in Fig. 6a, wastewater treatment supported the lower possibility of fouling with final results showing that COD removal efficiencies of 80%, which is enough to mitigate the impact of membrane fouling (Moser et al. 2018). The method of a hybrid membrane bioreactor system, which includes TiO₂/H₂O₂/UV as a post-treatment process, was shown to produce the best results among all the choices evaluated from the standpoint of chemical kinetics and biochemical kinetics (Moser et al. 2018).

Hairom et al., (Hairom et al. 2014); utilized ZnO nanoparticles in a membrane photocatalytic reactor (MPR) for the treatment of Congo red (CR) dye; schematics of the laboratory scale MPR are shown in Fig. 6b. They synthesized four types of ZnO via the precipitation of oxalic acid and zinc acetate solutions under stirring conditions in the presence of polyvinyl pyrrolidone (PVP). As anticipated, the ZnO-PVP-St demonstrated excellent MPR potential due to its strong photodegradation efficiency and low membrane flux drop. The optimum photocatalyst loading for the system was 0.3 g L⁻¹ under 20 g L⁻¹ dye concentration and pH 7 of the initial CR dye solution due to the effective surface area of ZnO-PVP-St and adsorption of UV light (Hairom et al. 2014). Wastewater containing dry-spun acrylic fiber (DAF) has been studied by Wei et al., (Wei et al. 2015); in a Fenton-sequencing batch membrane bioreactor (SBMBR) technique at bench scale (Fig. 6c). Fenton oxidation was utilized to pretreat the wastewater from the DAF polymerization process. Under the optimum circumstances of H₂O₂ 90.0 mM, Fe²⁺ 20.0 mM, 3 pH, and reaction time 120 min, the COD removal efficiency exceeded 47.0% and decreased the toxicity. Under the optimum conditions, the average

COD, NH₄⁺-N, and TN removal efficiencies reached 82.5, 98.4, and 74.6%, respectively (Wei et al. 2015).

MBR and UV-driven AOPs were combined to treat synthetic wastewater containing 100 µg L⁻¹ naproxen (NPX), 200 µg L⁻¹ bisphenol A (BPA), and 150 µg L⁻¹ sulfamethoxazole (SMX). The MBR setup included a sequencing batch reactor (SBR) with external filtration using track-etch membranes (10 nm, 50 nm, 100 nm) and a phase inversion membrane. TOC removal by SBR was 78–86%, while pollutant removal was 11% (NPX), 45% (BPA), and 6% (SMX). The best-performing membrane (10 nm) removed 11% NPX, 93% BPA, and 14% SMX. UV/PS (10 mM) with ZVI (25 µg L⁻¹) achieved complete mineralization in 30 min (Kanafin et al. 2023).

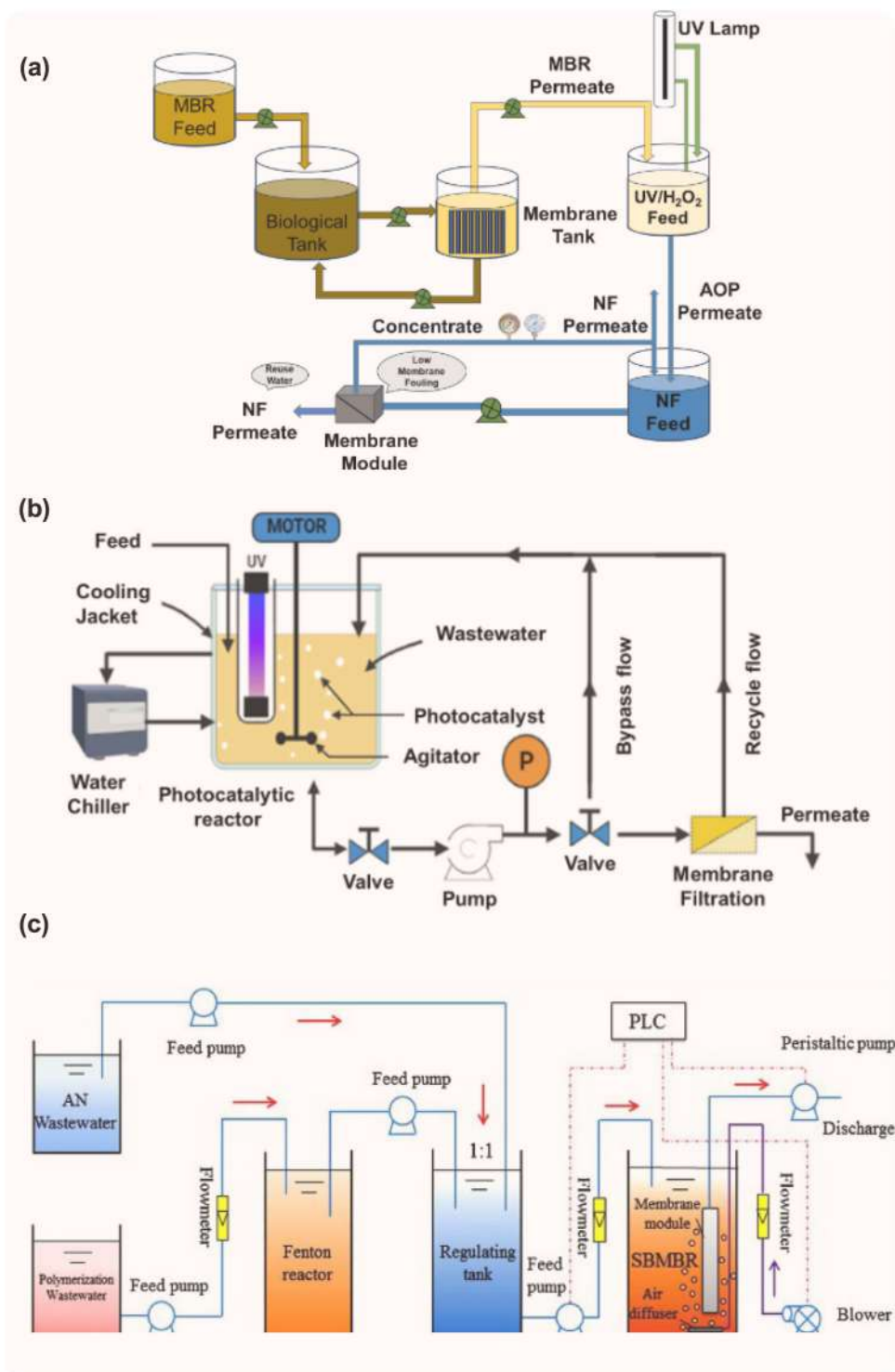
As a final evaluation of the MR/MBR system integrated by AOPs, it can be said that by effectively eliminating, degrading, biodegrading, and oxidizing poisonous, harmful, unneeded, and noxious compounds, satisfactory results have been provided for diverse discharges. The fact that membrane fouling, a significant barrier to treatment in the system that demonstrated the necessity for integration of MR/MBR with AOP, significantly decreased is another significant factor in the high removal performance of MR/MBR combined with AOPs. The system's smaller size, when compared to single AOPs, further emphasizes the necessity of integrating AOPs with the MR/MBR technique.

Membrane fouling: mechanisms and mitigation

Membrane fouling remains a significant challenge in Membrane Bioreactor (MBR) systems, primarily due to the accumulation of Extracellular Polymeric Substances (EPS) and Soluble Microbial Products (SMP) (Mannina et al. 2023). EPS, composed mainly of proteins and carbohydrates, is secreted by microbial cells and can deteriorate sludge flocculation, leading to increased membrane resistance. SMP, consisting of soluble organic compounds produced during microbial metabolism, accumulates on membrane surfaces, causing concentration polarization and the formation of dense fouling layers (Du et al. 2020). EPS and SMP can fill the gaps within microbial flocs, reducing porosity and increasing the specific resistance of the deposited layer, thereby exacerbating membrane fouling. EPS contributes to membrane fouling by forming dense gel-like structures on membrane surfaces, increasing resistance to water flow (Tang et al. 2025). Its hydrophobic nature enhances adhesion to membrane surfaces, promoting irreversible fouling. High concentrations of EPS result in reduced sludge floc permeability, thereby exacerbating cake layer formation and decreasing filtration efficiency (Hou et al. 2018). SMP plays a significant role in pore-blocking and concentration polarization. SMP components, particularly proteins and humic substances, are small enough to penetrate membrane



Fig. 6 (a) Schematics of direct (UV) and hydrogen peroxide-assisted (UV/H₂O₂) photolysis applied to MBR permeate as a pre-treatment for nanofiltration systems treating petroleum refinery wastewater; Reprinted with permission from Ref (Moser et al. 2018), Copyright [2018] Elsevier B.V., (b) Schematic of the laboratory-scale MPR, Reprinted with permission from Ref (Hairom et al. 2014), Copyright [2014] Elsevier B.V., (c) The flow chart of the Fenton-SBMBR system. Reprinted with permission from Ref (Wei et al. 2015) Copyright [2015] Elsevier B.V



pores, leading to internal fouling and flux reduction (Luo et al. 2021). Additionally, the interactions between EPS and SMP can lead to the formation of a highly compacted fouling layer, further hindering membrane performance.

One of the primary challenges in managing EPS and SMP fouling is their dynamic production within MBR systems. EPS concentration fluctuates with operational

conditions such as hydraulic retention time, sludge age, and organic loading rate (Abo et al. 2024; Wang et al. 2024). High sludge retention time can lead to excessive EPS accumulation, aggravating fouling tendencies (Petukhov and Johnson 2024). Similarly, SMP production varies based on microbial metabolic activities, making its prediction and control difficult. Another challenge lies in the limited

effectiveness of conventional fouling control strategies (Lin et al. 2024). Backwashing and chemical cleaning are commonly employed methods; however, EPS and SMP-related fouling often require more aggressive and frequent cleaning, which can degrade membrane lifespan and increase operational costs. The inefficacy of traditional methods calls for advanced control strategies, such as quorum quenching, which targets microbial signaling to inhibit excessive EPS production. Optimizing aeration intensity and implementing periodic relaxation techniques have been explored as potential mitigation strategies (Lin et al. 2024; Tang et al. 2025).

Cost analysis of membrane-based wastewater treatment technologies

The economic viability of membrane-based wastewater treatment technologies is a crucial determinant in their selection, encompassing factors such as capital expenditure (CAPEX), operational expenditure (OPEX), energy requirements, and long-term cost efficiency. Judd (2017) underscores the significance of CAPEX and OPEX in assessing the feasibility of membrane processes, particularly reverse osmosis (RO) and membrane bioreactors (MBRs) (Judd 2017). While these technologies are recognized for their high treatment efficiency, their overall cost-effectiveness is largely influenced by membrane durability, maintenance demands, and energy consumption. Kehrein et al., (2021) further elaborate on these considerations through a techno-economic analysis of membrane-based municipal wastewater reuse, demonstrating that although MBRs entail higher initial investments relative to conventional activated sludge systems, they present economic advantages over time (Kehrein et al. 2021). These benefits arise from reduced sludge generation, superior effluent quality, and opportunities for water reclamation, which help offset operational costs. A similar trend is observed in the techno-economic evaluation of MBRs for hospital wastewater treatment, which highlights the declining cost of membranes, improvements in energy efficiency, and advancements in fouling mitigation as key factors contributing to their increasing economic feasibility (He et al. 2024). Additionally, the integration of forward osmosis with membrane bioreactors (FOMBR) has been investigated in terms of economic performance, energy consumption, and carbon footprint. The study reveals that although FOMBR systems require higher upfront investment, their lower energy demands and reduced greenhouse gas emissions position them as both economically and environmentally sustainable alternatives to conventional microfiltration-based MBRs (Hamid et al. 2019).

A study on the techno-economic analysis of combining forward osmosis (FO), reverse osmosis (RO), and anaerobic membrane bioreactors (AnMBR) for municipal wastewater treatment and water production (2019) provides further

insight into the cost implications of hybrid systems. The findings suggest that while a closed-loop FO-RO-AnMBR system can achieve a minimum treatment cost of €0.81 per cubic meter at 50% FO recovery, higher FO recoveries increase overall treatment costs. This indicates that optimizing recovery rates is essential to maintaining economic feasibility (Vinardell et al. 2020). Collectively, these studies emphasize that despite the substantial capital investment associated with membrane technologies, their long-term economic benefits, such as reduced chemical usage, lower sludge handling costs, and potential for energy recovery, enhance their feasibility. Therefore, a comprehensive economic evaluation that considers both capital and operational and maintenance costs is essential for making informed decisions on selecting membrane-based wastewater treatment technologies. Further in-depth studies are needed to enhance our understanding of the cost analysis associated with these technologies.

Challenges and future perspectives

Membrane technology applications for wastewater treatment have grown significantly and are still rising. The operation of MBRs presents significant opportunities for improving specific filtration flux. However, the intensified membrane fouling observed during colder seasons remains a major challenge, necessitating further research to develop effective mitigation strategies (Turan 2025; Xu et al. 2023). MBR has little environmental impact as compared to traditional activated systems. Although the energy consumption of MBR is still more than that of conventional activated systems per volume of treated wastewater, the difference has been closing over time. Future full-scale MBR applications will have a difficult time effectively controlling fouling. It is crucial to optimize the hydrodynamic conditions based on the interaction between the membrane and the flowing media, as well as filtration-crossflow-circulation. The complexity of membrane fouling requires the development of more effective cleaning methods and chemicals. Developing more effective membrane-and-bioreactor combination modes, improved membrane scouring and biological aeration system designs, improvements in aeration modes, and finer control of the operation states are all necessary for effective aeration. As the most promising application fields are worth rethinking, more fair positioning in the application fields is also a challenge for MBRs.

The applicability of FO-based systems at a decentralized or centralized level and economic obstacles that significantly impact technology acceptability are two crucial factors for this concept. MD is a thermally based membrane separation technique that uses a microporous hydrophobic membrane to separate materials based on the idea of phase equilibrium.



The high thermal energy demand of the MD system is a significant drawback. By adding MD to current treatment methods, we may build a hybrid MD and pave the way for increasing its industrial usefulness. Appropriate membrane development is a key element that will promote the evolution of the hybrid MD system. MD can be readily linked with low-cost heat sources such as solar, geothermal, and industrial waste heat at optimum temperatures. An excellent method for producing high removal efficiency from a variety of wastewater with low energy consumption is the AnMBR. Even though there have been numerous attempts to gain a deeper comprehension of the AnMBR system's removal mechanisms for organic micropollutants, more work has to be done in this area. The development of an integrated AnMBR process is always appealing, but improving knowledge of the elimination of organic pollutants that could arise during pre- or post-treatment in conjunction with the AnMBR reactor could aid in optimizing reactor design parameters and accelerating the process.

The use of photocatalytic technology is widespread and has applications in numerous industries. In the future, additional studies are required to concentrate on the photocatalytic mechanism in the visible wavelength range in the research work of photocatalytic membrane reactors. For example, the visible spectrum of light ranges in wavelength from 400 to 800 nm. Using modified TiO_2 and other visible light-responsive photocatalysts should receive more focus, and the modified material should be a cost-effective, environmentally acceptable product. Studying membrane fabrication mechanisms with photocatalysts and developing a broadly accepted design theory of PMRs are crucial to future

research. Recent investigations on eMBRs have demonstrated that eMBRs can overcome the difficulties associated with membrane fouling in MBRs and the need for electricity for electrochemical operations. A novel method for applying an electric field in eMBR more successfully than with conventional electrodes is the development of conductive membranes. The effect of the reverse electric field on an anode's lifetime in an eMBR has not yet been investigated. One of the most promising technological approaches for effective water treatment and the secure discharge or potential re-use of wastewater effluents is the expanding application of AOPs. AOPs have some drawbacks, such as the substantial amounts of ferrous sludge produced by Fenton and related processes, the high cost of chemicals like ozone and hydrogen peroxide, UV/ozone procedures, etc. Process integration, which involves linking different AOPs to one another or other physical and/or biological processes, can help offset some of these constraints. Figure 7 explains the challenges associated with the hybrid membrane system and its potential future developments.

Summary and conclusion

In this paper, various membrane processes and reactor types, including membrane bioreactors with various hybrid forms, photocatalytic membrane reactors, electrochemical membrane reactors, and advanced oxidation and reduction processes, have been reviewed. These membrane reactor types are used in municipal and industrial wastewater treatment. Submerged membranes and external circulation

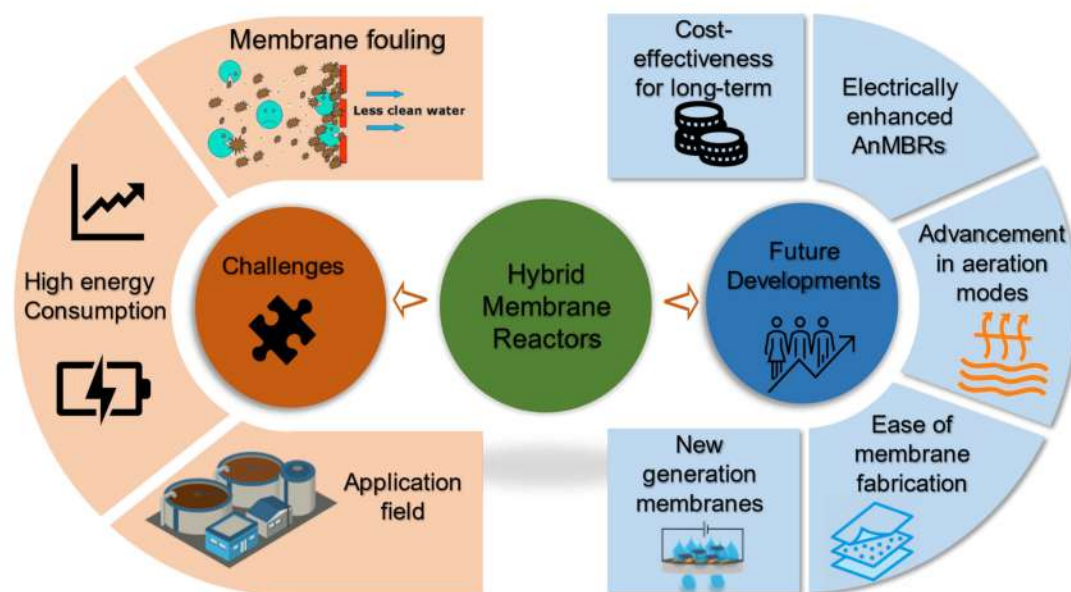


Fig. 7 Challenges associated with the hybrid membrane system and its potential future developments

are common MBR setups, and MBR technologies heavily rely on submerged MBR systems. Submerged MBRs are often operated at low differential pressure and well below the essential permeate flux to control fouling more easily. Since the membrane is closer and can be cleaned without interfering with system operation when using the side-stream configuration, fouled membranes require chemical cleaning. Replacing side stream fouled membranes is much simpler than replacing submerged membranes immersed directly into the reactor. AnMBRs are superior to "conventional" technology in several ways, particularly when treating toxic and concentrated wastewater and bridging the gap between high-rate anaerobic systems and conventional digesters. AnMBRs offer several benefits, including improved effluent quality, increased methane conversion, and decreased waste biosolids production. While AnMBRs hold promise for sustainable wastewater treatment and energy generation, the trade-off between their numerous advantages and associated challenges underscores the need for ongoing research to optimize their performance and economics. AnMBR integrated with FO membranes contributes to the generation of excellent-quality water and can accumulate phosphates and ammonia, thereby facilitating the recovery of potential nutrients. However, considering the high cost associated with FO membranes, these may find greater applicability in water reuse applications rather than the treatment of wastewater.

MD can concentrate solutions to their saturation point without experiencing a major flux decline, and is based on a temperature gradient established through a microporous hydrophobic membrane. The MD process can be carried out at temperatures that are normally below 70 °C and is propelled by a small temperature difference between the hot and cold solutions of just 20 °C. As a result, low-grade waste and/or alternative energy sources like solar and geothermal energy can be combined with MD systems to create a liquid separation system that is both economical and efficient in terms of energy use; however, next-generation membranes are required to deal with the wetting problem. With photocatalysis integrated into a membrane process, PMR is an efficient, economical, and environmentally friendly treatment technique with enormous promise to become a zero-waste process in the water and wastewater industry. A promising application of PMRs with immobilized photocatalysts in water and wastewater treatment results from increasing the photocatalyst surface ratio, which increases organic removal efficiency and improves photocatalyst stability by entrapping or coating photocatalysts on the membrane. Membrane fouling is the PMRs' major problem that results in a decrease in permeate flux and compromises the membrane's separation properties, thus necessitating frequent membrane replacement, and this is due to the presence of humic acids in the wastewater or photocatalyst particles.

Compared to standard MBR, electro-coagulation using stainless steel as the cathode and aluminum as the anode is particularly effective at removing metal and has a longer membrane life. For the treatment of wastewater from tanneries, pharmaceutical manufacturing facilities, and colored wastewater from the textile industry that is intended for zero discharge, MBR in combination with electro-coagulation is acceptable. The integration of the electrochemical process with MBR is an attractive alternative to addressing the problem of membrane fouling and recovering bioenergy.

AOPs and membrane filtration combinations offer a viable way for wastewater treatment to benefit from degradation and separation capabilities. Given the numerous relevant literature reports on the hybrid process's efficiency, AOPs integrated membrane processes might be a good substitute for their large-scale implementation. Depending on the desired efficiency level, AOPs can achieve more than 90% of organic pollutant removal efficiency in one-pot reactors, whether utilized as pretreatment, posttreatment, or integrated treatment. Catalytic membrane reactors have been developed to improve wastewater purification and reduce membrane fouling. Even though it can take a while to resolve the problems in the discussed techniques, there is no doubt that in the future, these hybrid membrane reactors will be more frequently used for more effective water and wastewater treatment and upgrading the existing municipal and industrial wastewater treatment plants.

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Data Availability The data will be made available on request.

Declarations

Competing interests The authors state that they have no known conflicting financial interests or personal relationships that could appear to have influenced the work.

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