Review Article

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Indones. J. Chem. Stud.
2025, 4(1), 35-45
Available online at journal.solusiriset.com
e-ISSN: 2830-7658; p-ISSN: 2830-778X

Indonesian Journal of Chemical Studies

The Potency of Photocatalytic Membrane Bioreactor for Wastewater Treatment: A Brief Review

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Received: 16 Dec 2024; Revised: 3 Feb 2025; Accepted: 25 Apr 2025;
Published online: 30 Jun 2025; Published regularly: 30 Jun 2025

Abstract— Membrane bioreactors (MBR) are a promising method for wastewater treatment that combines microbial degradation with membrane separation. MBRs offer efficient and sustainable wastewater treatment by combining biological processes with membrane filtration, providing high-quality effluents for reuse. The advantages of MBRs, such as their compact design, reduced sludge production, and water recycling potential, make them increasingly significant in addressing global water scarcity and pollution challenges. Nevertheless, the issue of biofouling persists as a notable obstacle, primarily caused by the interplay of bacteria, membrane surfaces, and the release of extracellular polymeric substances (EPS). Integrating photocatalysts into MBR membranes offers a new method to reduce fouling. This study provides a comprehensive overview of current research on the membrane modification using photocatalysts in MBR systems, focusing on the existing challenges and prospects in this field. Despite these potential advantages, research on improving MBR membrane performance through photocatalysis is sparse. To ensure the sustainability of this technology, it is essential to consider important factors, such as reactor configuration, kinetics, fouling processes, economic feasibility, and scaling issues.

Keywords— *Antifouling; Biofouling; Bioreactor; Membrane; Photocatalyst*

1. INTRODUCTION

Membrane bioreactors (MBRs) are hybrid system that integrate microfiltration or ultrafiltration membranes with biological processes. This method facilitates the decomposition of trash or biomass within the bioreactor tank. Simultaneously, the membrane module separates the treated water and microorganisms, yielding a thoroughly treated effluent appropriate for reuse or environmentally safe discharge. The membrane pore size, selectivity, permeation rate (flux), and membrane surface features are crucial indications in the development of membranes. The primary distinction between MBRs and conventional treatment facilities is the use of membranes to segregate treated wastewater from solid waste [1].

In recent years, membrane bioreactors (MBR) have garnered significant interest due to their ability to generate effluent with exceptional quality. Wastewater treatment is presently regarded as a mature technology. MBR systems often exhibit diverse microorganisms rather than a singular bacterium. EPS comprises carbohydrates, humic compounds, and proteins [2]. In addition to EPS in the MBRs, which leads to bacterial adherence on the membrane surface, the buildup of microorganisms on the surface and within the porous membrane also contributes to membrane biofouling [3].

The membrane's hydrophobic qualities intensify the adsorption of EPS on its surface, therefore hastening membrane biofouling. Membrane biofouling leads to a reduction in filtration efficiency, a decrease in membrane durability, and an increase in operational expenses [4]. Membrane fouling can be classified into two categories: reversible and irreversible. Concentration polarization and forming a loose cake layer on the membrane surface are common causes of reversible fouling. In these cases, transmembrane flow can be restored by employing mechanical or chemical cleaning methods. Irreversible fouling occurs when pollutants significantly interact with the membrane materials, causing them to adsorb within the membrane's pore channels or on its surface. In such cases, restoring flow physically or chemically is generally impossible. Membrane biofouling controls were implemented by employing chemical pretreatment of wastewater treatment and modifying the membranes with bactericides, as described by [5].

Nevertheless, these approaches create more pollutants, pose environmental hazards, and incur

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DOI: 10.55749/ijcs.v4i1.63

additional expenses for remediation. Applying hydrophilic modifiers, such as polymer material or organic nanoparticles, to the membrane surface can significantly improve its ability to resist fouling [6]. Membranes with hydrophilic properties, such as polyvinyl alcohol, polyethylene glycol derivatives, and zwitterionic polymers, have been shown to enhance membrane flow and effectively prevent membrane fouling. However, the solutions mentioned only target the reduction of organic pollution and bacterial adherence, which appear ineffectual regarding irreversible membrane fouling [7]. Once foulant deposition occurs on the membrane, modifying its hydrophilicity becomes ineffective. This is because subsequent fouling is primarily driven by the interaction between newly deposited foulants and those already present. Therefore, new strategies are needed to remove and degrade the deposited foulants [8]. Thus, it is imperative to discover cost-effective alternate pathways to mitigate membrane biofouling.

Photocatalytic membranes combine membrane separation and photocatalysis to enhance filtration efficiency, degrade organic pollutants, and reduce membrane fouling. These membranes incorporate photocatalysts, such as TiO_2, g-C_3N_4, or ZnO, which absorb light energy to initiate photocatalytic reactions. When exposed to light with energy equal to or greater than the photocatalyst's bandgap, electron-hole pairs (e^-) and (h^+) are generated. These charge carriers play a crucial role in redox reactions, where the holes oxidize organic contaminants, and electrons participate in reduction reactions, often producing reactive oxygen species (ROS), like hydroxyl radicals (•OH) and superoxide anions (O^{2-}). These reactive species effectively degrade organic pollutants, break down biofouling agents, and prevent membrane clogging, thus improving membrane longevity and efficiency. The integration of photocatalysts into membranes can be achieved through surface coating, blending, or embedding within the membrane matrix. The effectiveness of photocatalytic membranes depends on factors such as light source intensity, photocatalyst type, and operating conditions, making this technology a promising solution for sustainable water purification and environmental remediation [9], [10].

Membranes can be enhanced with reactive nanomaterials, such as TiO_2, ZnO, Fe_2O_3, and FeOCl, to improve their self-cleaning characteristics in certain circumstances [11]–[14]. By incorporating TiO_2 into the membrane, the membrane's lifespan can be extended by avoiding the accumulation of contaminants on the membrane surface, a process known as membrane fouling. Following the phase inversion, nanoparticles exhibit a distinct outcome compared to polymers. While nanoparticles tend to remain within the structure of the membrane and obstruct the pores, polymers may be eliminated from the membrane by dissolving them in water. Due to the contradictory impacts of the nanoparticle, accurately forecasting the membrane's performance alteration is difficult. Hence, further investigation is necessary to gain a more profound comprehension [15]. Despite several efforts to combine membranes with photocatalysts, there is still room for improvement in using photocatalytic membranes in bioreactor membranes. The presence of bacteria, algae, and fungus in bioreactor membranes poses difficulties in using photocatalysis. This review paper briefly summarizes the progress made in the field of membrane bioreactors for wastewater treatment and hightlights the advancements in merging photocatalysts and membranes within membrane bioreactor technology. This article also summarizes the possibilities and difficulties involved in advancing photocatalytic membrane bioreactors, with a particular focus on Indonesia.

2. MEMBRANE BIOREACTOR

Wastewater treatment employing biological processes, typically activated sludge, has not been able to decompose organic micropollutants such as persistent organic pollutants (POPs). The capacity of a biological treatment is determined by the properties of the molecules involved, such as their chemical structure, sorption capacity, hydrophobicity, and son, as well as the operational parameters of the wastewater treatment plant's biological process, including hydraulic residence time and sludge residence time. These methods include membrane technology [16], adsorption [17], biodegradation [18], and chemical oxidation [19], such as Fenton, Electrochemistry, Sonication, Persulfate, and Ozonation [20]. Each of these strategies has its limitations.

High salinities continue to pose challenges for organic adsorption, such as susceptibility to certain functional groups, limited specific surface area, and the need for expensive and complex production methods. The elevated salinity can significantly affect the activity and population of bacteria in biological technologies. Secondary pollution and ineffective organic removal hinder the effectiveness of chemical oxidation, whereas membrane technologies are greatly affected by membrane fouling and high costs. The cost of treating wastewater from shale gas remains a significant obstacle in research initiatives [16]. Biological pretreatment is a cost-effective approach that is widely recognized for its affordability. This approach eliminates the requirement for chemical handling or treatment of organic matter absorbed or precipitated onto the media. Membrane separation technology is a prevalent water treatment process employed across several sectors. The process efficiently segregates solids, dissolved compounds, and colloidal particles from wastewater by selectively separating components depending on their size, molecular weight, charge, or other characteristics [21]. Membrane separation often necessitates lower energy use than other separation techniques, such as distillation or evaporation. Operating at ambient or moderate pressures and temperatures, it is both more energy-efficient and more cost-effective in the long term. In addition, the membrane separation processes can operate continuously, providing consistent and uninterrupted separation efficiency. This condition is particularly beneficial for sectors that require uninterrupted production or treatment operations. Some studies have demonstrated that using MBR to enhance biological processes is more efficient in removing pharmaceuticals than activated sludge.

The practical use of MBR to remove organic matter from wastewater generated during shale gas extraction has encountered challenges. However, several studies have demonstrated that MBR is a feasible and captivating technique with significant potential for treating organic matter in wastewater derived from shale gas production [22]. A MBR facility, which integrates membrane filtration with biological treatment, is a feasible alternative to the traditional wastewater treatment plants (WWTPs). Although the MBRs have a reduced physical space need and generate superior-quality effluents, they also entail increased expenses for operation and maintenance. These expenses are linked to the membrane systems that require frequent replacement of short-lived membranes. An MBR plant can be developed in a side-stream configuration or immersed layout. Side-stream MBRs have a membrane unit outside the bioreactor, whereas immersed MBRs have a membrane unit inside the bioreactor [23]. A typical MBR plant consists of many components, including a backwash cleaning tank, an air blower for aeration, a sludge recirculation, and chemical dosing system, a mechanical filter for pretreatment, and separate tanks for anoxic, aerobic, and anaerobic biological treatment. Permeability and transmembrane pressure (TMP) are crucial factors for proper functioning of membranes. Permeability, a measure of the efficacy of filtration through the membrane, is obtained by dividing the permeate flow by the TMP. Temperature is the primary factor that propels filtration. The MBRs may operate in two modes: (1) maintaining a constant flow of permeate while varying the TMP and (2) maintaining a constant TMP while varying the flux of permeate [24].

The increasing presence of highly hydrophobic compounds in wastewater presents a significant risk of toxicity, which poses a grave threat to the ecosystem. Membrane fouling, caused by the clogging of MBRs, remains a substantial barrier to their broader and more established use in industrial applications. The detrimental effects of biofouling on MBRs encompass changes in structure, function, and organization, pore blockage, and subsequent microbial degradation. The membrane surface is coated with deposits of micacid and bio-cake. During continuous operation mode, fouling of the membrane bioreactors (MBRs) leads to a rise in TMP, decreasing permeate flux. Consequently, the cost of replacing and cleaning membranes rises. MBRs offer several advantages, as displayed in **Table 1**.

Table 1. The advantages of MBRs over conventional methods

Advantages	Disadvantages
Smaller bioreactor size	The main problem is fouling.
No restriction on mixed liquor suspended solid concentration (MLSS)	Increased operational costs brought on by the price of the membrane and antifouling techniques
With the help of Solid Retention Time, the permeate water's quality can be assessed (SRT).	Complex process
Longer SRT operation increases wastewater efficiency	High foaming propensity caused by the larger aeration demand of MBR
Superior effluent without sedimentation and high-quality effluent	High power consumption.

Membrane biofouling refers to the typical occurrence of membrane fouling due to the buildup of biological microorganisms. Membrane biofouling is categorized into two types: microfouling and macrofouling. Microfouling refers to the buildup of unicellular and multicellular organisms, whereas macrofouling is produced by more significant organisms, such as algae. Resolving membrane biofouling is highly challenging. Membrane biofouling manifests through three primary stages: adhesion, dissemination, and biofilm development. The regulation of biofouling is influenced by some factors such as the specific microorganism involved, the surface properties of the membrane (including material, charge, hydrophobicity, roughness, and porosity), and the characteristics of the feed (such as pH, temperature, dissolved organic/inorganic matter, and flow rate). Adsorption plays a crucial role in the development of biofouling. Bioreactor membranes incorporating bacteria are prone to the bacterial adherence on the membrane surface. The bacteria release a complex molecule called EPS throughout this procedure. The EPS matrix often comprises organic components, including proteins, nucleic acids, lipids, polysaccharides, and inorganic elements like minerals and clays. Proteins are the primary contributors to membrane biofouling among EPS formers due to the presence of functional groups such as carboxyl, amino, and methyl groups. The functional groups present in proteins affect their hydrophilicity and the adherence of

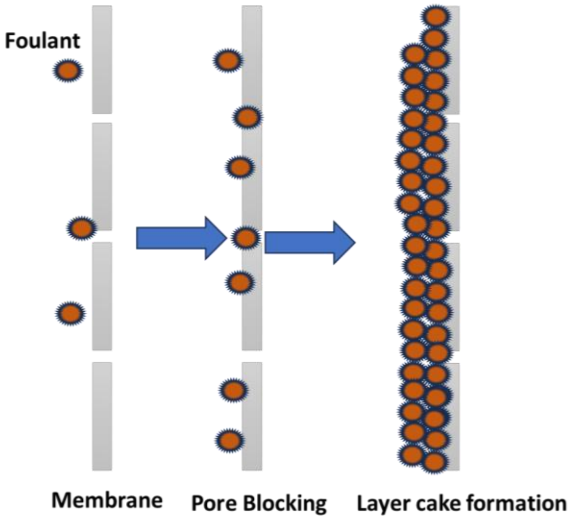

Fig. 1. Membrane fouling mechanism

EPS to the membrane surface through van der Waals interactions and hydrogen bonding [25]. **Table 2** summarizes studies that have successfully addressed the fouling issues in MBRs.

The interaction between foulants and membranes can be divided into two stages (**Fig. 1**) . The first stage involves the interaction between the membrane and foulant, resulting in primary pore blocking. The second stage includes the interaction between the foulant and the membrane, forming a gel layer. This gel layer can contain various substances, such as surface foulant layers, exopolysaccharides (EPSs), organic polysaccharides, proteins, oils, polyelectrolytes, and humic acids. The primary constituents of most biopolymers (>100 kDa), which are believed to be the primary substances causing fouling in low-pressure membrane filtration, are polysaccharides. Polysaccharides exhibit a greater propensity for membrane rejection and biodegradation compared to proteins and humic acids due to their large size and gelation properties.

The significant tendency of polysaccharides to accumulate fouling is directly linked to their substantial dimensions and gel-forming properties. The cross-linked chain configurations induce gel formation in polysaccharides, and divalent and multivalent cations further enhance this gelation process. This phenomenon is known as impermeable gels and serves as a connection between carboxyl groups and polysaccharides. EPS and SMPs, acting as foulants, can enhance component and intermolecular interactions [8], [26]–[28].

EPS significantly impacts the ability of reverse osmosis membranes to reject salt and the pace at which water flows through them during the biofouling process. EPS biofouling deposits have a detrimental influence on the permeate flow by improving the hydraulic resistance to flow. EPS is responsible for about ninety percent of the biofouling material bacteria produced. Thus, the molecular components present in EPS are identical to those found in microbes, encompassing various polysaccharides, proteins, lipids, and nucleic acids. In Pseudomonas aeruginosa, around 60% of the EPS consists of polysaccharides, while proteins comprise about 5% of the entire biomass. In contrast, in Escherichia coli-based biofouling, polysaccharides account for roughly 10% of the overall biomass, while proteins make up approximately 55%. Therefore, it can be inferred that the presence of mixed population in biofouling leads to the formation and buildup of more intricate EPS, affecting both biofouling and the choice of antibiofilm strategies employed [5].

Membrane biofouling is a significant limitation in the use of membrane bioreactors. The fouling that arises hinders the functioning of the membrane, resulting in losses in the application of the bioreactor membrane. Several initiatives have been undertaken to rectify this inadequacy. One method involves incorporating a photocatalyst inside the membrane. However, unlike regular membrane reactors, membrane bioreactors need specific considerations due to the participation of microorganisms. The photocatalyst's reliance on UV/visible light might harm the microorganisms present in the reactor. In addition, photocatalysts can break down germs and microbes. Hence, incorporating a photocatalyst into the bioreactor membrane presents inherent difficulties. Multiple studies have documented efforts to include photocatalysts in the membrane bioreactors.

Membrane Bioreactors (MBRs) are increasingly being adopted in Indonesia to address the challenges of wastewater treatment in the municipal and industrial sectors. By integrating membrane filtration with biological processes, MBRs offer efficient contaminant removal and produce high-quality effluent suitable for reuse. This technology is particularly beneficial in urban areas with limited space, as MBR systems have a smaller footprint than conventional treatment methods—companies like PT. Hydromart Utama Indonesia and Hydromaster Indonesia are actively involved in implementing MBR solutions nationwide. Research institutions in Indonesia are also contributing to the advancement of MBR technology. Studies have demonstrated the effectiveness of MBRs in treating various types of wastewater, including greywater. For instance, a study highlighted that MBRs could reduce pollutants such as Biological Oxygen Demand (BOD) by 93%, Chemical Oxygen Demand (COD) by 94%, and ammonia by 92%, making the treated water suitable for reuse. These findings underscore the potential of MBRs in enhancing wastewater treatment efficiency and supporting water conservation efforts in Indonesia. Despite the promising applications, challenges such as high operational costs, membrane fouling, and the need for technical expertise persist. To overcome these obstacles, ongoing research is focused on optimizing MBR configurations and developing cost-effective solutions tailored to local conditions. Collaborations

Table 2. The fouling mitigation in MBR [23]

Novel strategy	Performance in minimizing fouling	Result	Ref
Membrane structute modification	Modification of membrane using photocatalyst, MOF, etc	• Long-term operation results in improved antifouling characteristics, a slower rate of flux depletion, higher fouling rejection, a lesser increase in TMP, and lessened od membrane fouling.	[29]
Microbial community properties	Evaluation of dissolved organic carbon contribution and microbial dynamic to membrane fouling control	• Increasing COD removal • One of the crucial factors in fouling control is maintaining and managing microbial diversity. • Due to its high abundance in the fouled membrane, Xanthomonadaceae may be connected to fouling. • Regarding the mitigated membrane data, Chitinophagaceae and Candidatus Promineo filum played a key role in reducing fouling due to their abundance in mitigated fouled MBRs.	[30]
Modification of biomass properties	Evaluation of the performance of MBR and fouling characteristics by adding nanoparticles as adsorbents	• Increased COD elimination in both systems as a result of NPs' ability to bind to organic materials • Better performance of NP1 in removing EPS and SMP compared to the original system (49% and 66% deduction in EPS and SMP for NP1 while for NP2 was 38% and 54% respectively)	[28]
Hydrophilic membrane surface modification	Assessment of Antifouling performance of hydrophilic modification for anammox since it showed a promising strategy as antifouling in aerobic and anaerobic MBR	• Mh has greater gel layer resistance than Mp. Forming a thin, tight gel layer on Mh while Mp was thick and loose. • Rapid flux reducing short filtration cycles in the long-term operation of anammox MBR	[31]
Optimizing operating condition	Evaluating the effect of temperature on the methanogenic activity in An-MBR	• Decreasing energy usage as a result of liquids' reduced viscosity as a result of a drop in temperature. • Increasing flux by decreasing temperature	[32]
Membrane cleaning method	Effect of granular activated carbon with the recycling of liquid to control fouling as a replacement for biogas sparging	• Providing a lot of surface area for the formation of biofilm • Low energy consumption • Effective fouling mitigation	[33]
Pretreatment of feed	Applying the advanced oxidation technique as a pretreatment to mitigate the fouling propensity of the membrane and comparing its effect with the coagulation technique	• Both approaches show promise in terms of lowering overall fouling resistance. Primarily as a result of the very high MW biopolymers breaking down • Comparing the coagulation method to the advanced oxidation process, the irreversible fouling type produced by the coagulation method is less severe.	[34]

between government agencies, private companies, and research institutions are essential to promote widespread adoption of MBR technology, ultimately contributing to sustainable water management and environmental protection in Indonesia.

3. PHOTOCATALYST MEMBRANE (PM)

Membrane separation is a physical procedure that effectively separates contaminants while preventing deterioration. In addition, fouling, which refers to the accumulation of materials or particles on the surface or in the membrane's pores, can reduce membrane separation efficiency. In addition, certain elements may build deposits on the surface of the membrane, resulting in scaling. This scaling lowers the performance of the membrane and requires regular cleaning or replacement of the membrane [35]. A technique integrating catalysis and separation into a single unit is crucial to ensure dependable water purification, even if it cannot completely eradicate all micropollutants. In this scenario, many toxic or resistant organic substances are consistently released into soils, streams, and other natural ecosystems. Utilizing state-of-the-art chemical oxidation technology, the successful conclusion of this biological process shows excellent potential for future advancements. Advanced oxidation processes (AOPs) are widely recognized for their exceptional efficacy in treating persistent wastewater [36]. This technology is ecologically safe and can remove a wide range of contaminants without being selective. The aqueous-phase oxidation method, known as AOPs, is mainly used to generate hydroxyl radicals. These radicals are highly effective oxidants, second only to fluorine, and can remove many organic contaminants altogether. Under specific working circumstances, AOPs generate a substantial quantity of hydroxyl radicals. Studies have demonstrated the effectiveness of solar photocatalytic oxidation and other advanced oxidation strategies [20].

Photocatalysts used in membrane technology are commonly called photocatalytic membranes (PMs). Two methods are used to include photocatalysts into membrane technology: the slurry type, where the photocatalyst is disseminated in the feed solution, and the deposition type, where the photocatalyst is put in or on the membrane. Through diligent work and strategic development, PMs have emerged as a promising and effective approach to improving membrane quality, addressing doubts within the community. Multiple studies have shown the deposition of photocatalysts in membranes, demonstrating their ability to enhance membrane performance.

Hastuti et al. (2022) effectively manufactured a photocatalytic membrane composed of titanium dioxide ($TiO2$) and carbon nanotubes (CNTs) coated on polyacrylonitrile (PAN) nanofibers. The addition of carbon nanotubes (CNTs) to titanium dioxide (TiO_2) has been demonstrated to alter the energy difference between the valence and conduction bands of TiO_2, known as the band gap, from 3.15 to 2.76 electron volts (eV). This modification enhances the ability of TiO_2 to catalyze chemical reactions when exposed to visible light. In this work, the researchers employed LED light as the visible light source. According to the paper, including TiO_2/CNTs into the PAN membrane significantly improve the removal of the Methylene Blue (MB) color, increasing the performance from 60 to 95%. Incorporating TiO_2/CNTs into the PAN nanofiber membrane eliminates the need for a separate photocatalyst separation procedure from the aqueous medium after treatment. PMs have excellent stability, with just an 11% drop after being reused 5 times [37].

A resilient Zr/TiO_2-SiC membrane is effectively created by spray coating. The membrane exhibits high resistance to rhodamine B dye wastewater, with a rejection rate of 80% over 4 h when exposed to UV light. The membrane is utilized in the fixed-bed membrane reactor. The membrane performance exhibits an 11% decrease in rejection after being reused for the fifth time, and a noticeable reduction in mass is noticed during the experiment. Nevertheless, no assessment is currently available that evaluates the long-term operational efficiency of the membrane [38].

The PM reactor can be operated in either dead-end or cross-flow modes. During dead-end mode, the feed solution is compelled to pass through the membrane at a certain pressure. As the solution traverses the membrane, it undergoes filtration, causing the pollutant to be retained on the membrane surface. This mode exhibits many disadvantages, including a quick fouling process caused by the rapid buildup of pollutants and the potential for increased membrane damage due to the membrane pressure. In a cross-flow membrane reactor (**Fig. 2**), the feed solution, which is in motion over the membrane surface, will permeate through the membrane due to gravitational forces. The water that flows through the membrane results from permeation, which occurs after the membrane has been filtered [10]. The lateral motion of the water reduces the accumulation of pollutants on the surface of the membrane. Over time, contaminants will gradually build up on the surface of the membrane. The photocatalyst is anticipated to possess the capability to break down pollutants that build on the surface of the membrane, thereby minimizing the obstruction of membrane holes caused by pollutants.

Hastuti et al. (2023) have also documented the application of photocatalytic membranes in a cross-flow reactor. Using a cross-flow membrane, TiO_2/CNT membranes are applied onto PAN nanofibers to treat MB dyes. The investigation findings showed that the inclusion of TiO_2/CNT in the PAN nanofiber membrane effectively prevents fouling, resulting in a 95% rejection of MB over 8 h. Furthermore, the membrane remains stable and performs well for 80 h [15]. The research on the combination of photocatalyst and membrane in PM membrane reactor is presented in **Table 3**.

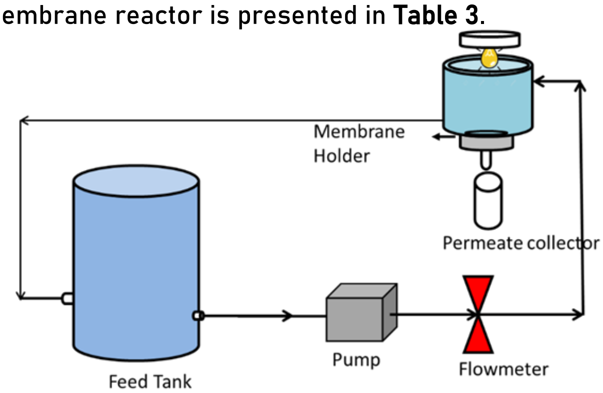

Fig. 2. Configuration of Cross-flow PM reactor

Based on **Table 3**, it can be concluded that the use of photocatalyst membranes still focuses on UV light. Even though UV light is minimal in nature, this is a drawback when applying PM on a broader scale. Although several researchers have attempted to develop active PM under visible light, their development still requires broader studies. In addition, several studies have reported the presence of photocatalyst leaching when membranes are used. Leaching occurs due to weak interactions between the substrate membrane and photocatalyst. How the membrane synthesis route also affects the leaching potential of the photocatalyst. PM fabricated using the coating method usually exhibits higher leaching potential because the photocatalyst is present only on the membrane surface.

Meanwhile, photocatalysts fabricated by blending the substrate will have a lower leaching potential [48].

Corredor et al. [49] reported the leaching of RGO/TiO_2 PM deposit on the Nafion membrane using dip-coating fabrication. While leaching is significantly reduced in solvent casting and spraying methods.

Tabel 3. Summarized of PM in wastewater treatment

Material	Membrane performance	Ref
Ag/Graphene oxide (GO)/Titania nanotube (TNT) on celluloce membrane	Degradation MB 65% in 400 min but no information in permeate rate.	[39]
metallophorphyrin-poly(vinylideneflouride) (PdTFPP-PVDF).	Degradation MB 60% under UV light but no information for permeate rate.	[40]
TiO_2/Al_2O_3 membrane	Degradation MB 80% (UV light) for 300 min.	[41]
Ag/TiO_2 nanofiber	Degradation MB is 80% in 30 min under sun-light irradiation, and the permeate rate is 7 LMH. Mode dead-end.	[42]
Alginate-TiO_2 nanofibe	Degradation Methyl Orange (MO) 40% in cross-flow reactor, permeate rate 5.8 LMH.	[43]
Ag-TiO_2/Membrane alumina	Degradation Rhodamine B 100% in UV light. Permeate rate 123 LMH. Mode dead-end.	[44]
N-TiO_2/Ceramic membrane	Degradation MB and MO is at 57% and 29%, and the permeate rate is 38,18, and 34,31 LMH. Mode dead-end.	[45]
TiO_2/Cellulose membrane	Degradation MO is 65% (UV-light) and 19% (visible-light), with a permeate rate of 90 and 81 LMH. Mode dead-end.	[46]
TiO_2/Ceramic membrane	Degradation Direct Black (DB) 72% (UV light), dye rejection (%R) 82%, Permeate rate 82 LMH.	[47]

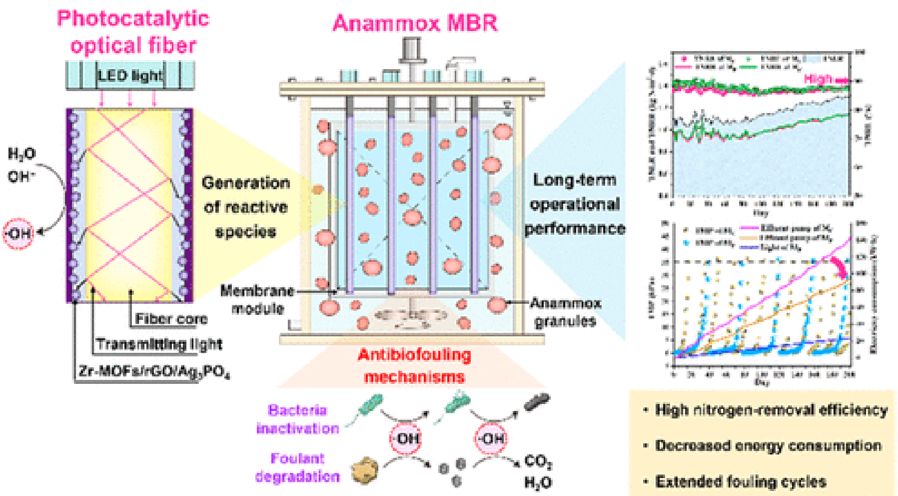

Fig. 3. The Zr/MOFs/rGO/Ag_3PO_4 on POF membrane for Annamox MBR [51] (Reprinted with permission from [6]. Copyright 2023 American Chemical Society)

However, the effect of adding photocatalysts into membranes for waste processing still needs to be developed, especially for applications with longer operation times. One of the advantages of using this membrane is that the gap between the laboratory and industry is narrow enough. This means that applying this membrane makes it easier to scale up to an industrial scale. However, efforts to optimize membrane performance still need to be made. One of them is to improve photocatalyst performance. The degradation rate must continue to be optimized because the accumulation of pollutants on the membrane surface will continue in line with the operating time. If the degradation rate is much lower than the accumulation rate of pollutants, the photocatalyst will be quickly covered by pollutants and cannot work.

The photocatalyst known as Photocatalytic Optical Fibers (POFs), which is described as fibril-coated on the surface of optical fibers (OFs), can be anchored on membrane surfaces. In POFs, the OFs can provide light transmission and photocatalytic support. As a result, photocatalyst agglomeration is reduced, and the light loss brought on by membrane filtration turbidity is avoided. It happens because light enters the inner core of the OFs and travels straight to the coated photocatalyst. Ni et al. [50] recently synthesized the eco-friendly photocatalytic antifouling technology for membrane bioreactors using POFs. Applying POF to MBR minimizes fouling by up to 137% compared to MBR and saves up to 18% of the energy. The Zr-MOF/rGO/Ag_3PO_4 photocatalyst deposited on POFs showed excellent performance during 202 days of operation (85.3-90.4%). Visible light is applied only inside the membrane (**Fig. 3**) so that it does not cause bacterial proliferation by light.

This method is a breakthrough to minimize bacteria proliferation due to light exposure. In addition, a configuration like this also increases the effectiveness of the photocatalyst because more of the photocatalyst can access light. Compared to only being irradiated on the top surface, this configuration is more effective in photocatalyst performance.

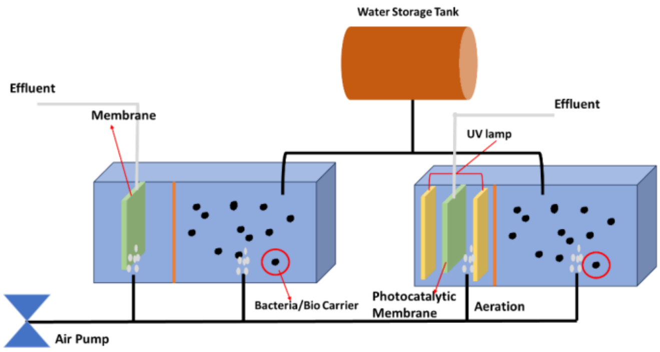

Fig. 4. Membrane Bioreactor configuration with nanomaterial-modified membrane.

Luo et al. [52] have reported the antifouling behavior of photocatalytically modified membranes in a moving-bed bioreactor for wastewater treatment. The PVDF membrane is modified with the reactive nanomaterial TiO_2, ZnO, Fe_2O_3, and FeOCl to remove TOC and NH_4^+-N. The membrane shows that the cake layer formation is reduced by 83% and pore blocking by 88%, indicating the antifouling behavior. The operation condition is illustrated in **Fig. 4**. Here is the description: (1) Influent apparatus: The wastewater characteristics are consistent with those of previous studies. Fresh wastewater is stabilized in a water storage tank for 24 h and enters the reactor as an influent through a flow pump. A flow pump is used between the water storage tank and the reactors to control the water level in the two reactors. Aeration establishment: At the bottom of the reactor, air (1.5 L min-1) is injected using a microporous aeration tube to provide dissolved oxygen for microbial growth and to keep the mixed solution flowing. (2) Effluent apparatus: The effluent is obtained by biodegradation and photocatalysis in the reactors and then discharged through the membrane module under the intermittent suction provided by a peristaltic pump. The intermittent operation of the peristaltic pump is controlled using a time relay system to reduce membrane fouling. The relaxation and suction times are 2 and 8 min, respectively. Adjusting the pump's speed maintains the effluent's flow rate at 15 LMH. The modified membrane is prepared via a layer-by-layer approach by coating TiO_2/poly(sodium styrene sulfonate) (PSS) layers. The fabrication processes and properties of the TiO_2/PVDF-modified membrane have been previously reported. Since the modified membrane exhibits photocatalytic activity, two UV lamps are placed on both sides of the photocatalytic reaction [52].

The modified membrane, owing to the high hydrophilicity, easily forms a water film on the membrane surface and prevents the hydrophobic pollutants from depositing on the modified membrane surface (**Fig. 5**). Under the same membrane performance, the impact of the photocatalytic activity on the TMP has been discussed. On the 33rd day of observation, the TMP of the modified membrane without UV light irradiation increases substantially, while the TMP of the modified membrane with UV light irradiation rises gradually. Without UV light irradiation, it takes 35 days to reach a TMP of 40 kPa, whereas it takes 43 days with UV light irradiation. Membrane fouling is significantly influenced by photocatalysis. During the membrane filtration process, TiO_2 has been found to degrade foulants.

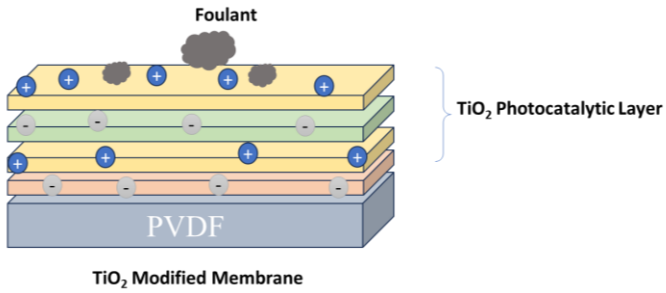

Fig. 5. TiO_2/PVDF-modified membrane configuration

Research on membrane modification in MBR remains rare. Therefore, the potential to conduct studies in this field is still very high. Moreover, new strategies for integrating the light source and filtration apparatus are needed. Due to the membrane's opaque construction, only a small portion of the membrane can be lit by the lamp [53]. This prevents light from penetrating the membrane. As a result, the photocatalyst reaction occurs only on the membrane's surface and becomes progressively restricted as pollutants accumulate. Therefore, it is essential to develop new varieties of membrane modules that are mechanically resilient for pressure-driven functioning and optically transparent (for external lighting) or equipped with internal light sources.

Zhang et al. have recently fabricated transparent g-C_3N_4 attaching to a porous cellulose film membrane (P-RCF@g-C_3N_4) using the ice crystal template method (ICT). Due to the P-RCF@g-C_3N_4 membrane's strong forward scattering ability, the haze effect significantly aids the propagation of light. The photon reaches the g-C_3N_4 layer with randomly scattered angles after emission through the transparent paper with the high optical haze, resulting in increased light absorption. Based on the results, the P-RCF@g-C_3N_4 membrane also exhibits an enhanced performance (62.1%) compared to the bare g-C_3N_4/CA membrane (53.7%) during the 80 min filtration for Cr(IV) wastewater treatment in fixed-bed photocatalytic membrane reactor (PMR). The membrane also shows high stability by maintaining its performance in the reusability test (a decrease of 10% after the third use) [54].

Another strategy has been reported by Yang et al. [24]. A Hollow fiber CNT membranes are used for electro-assisted aerobics MBR. The electric current applied to the reactor causes an increase in TMP and has a better temperature recovery (95%) for 100 days of operation. This is due to the repulsion of EPS by electrostatic forces, which inhibits the formation of a layer on the membrane surface. CNT hollow fiber does not show any photocatalytic activity. However, the route strategy proposed in this study is very attractive for increasing the lifetime of the membrane. There is a need for further research on this strategy.

4. COST-EFFECTIVENESS OF MEMBRANE BIOREACTOR

Membrane Bioreactor (MBR) technology has gained significant attention in the wastewater treatment industry due to its ability to produce high-quality effluent and its relatively compact footprint. While the capital costs can be higher than those of conventional activated sludge systems, MBRs offer unique advantages that often justify the investment. These advantages include smaller plant size, lower sludge production, and higher level of pathogen removal. Furthermore, the reduction in footprint is particularly beneficial in regions where land costs are high, offsetting some initial financial outlay with long-term savings [55].

One of the most notable cost considerations in MBR systems is the purchase and replacement of membranes. Membranes can be expensive, and their lifespans vary depending on some factors, like influent quality, maintenance practices, and operating conditions. Over time, operators need to replace aging or fouled membranes to maintain consistent performance. However, the membrane replacement cost has been steadily declining due to technological improvements and economies of scale in production, making MBRs more feasible for a broader range of applications.

Energy consumption is another key aspect of MBR technology's cost-effectiveness. MBRs can require higher energy inputs than conventional systems, primarily because of the need for aeration and membrane scouring to prevent fouling. Despite this higher energy demand, recent advancements in membrane materials and improved module design have helped reduce overall energy consumption. When coupled with optimized operational strategies and energy recovery methods, MBR systems can become increasingly energy efficient, further enhancing cost-effectiveness over the plant's lifecycle.

Lastly, the high-quality effluent produced by MBR systems can yield additional economic and environmental benefits. Treated water can often be reused for irrigation, industrial processes, or groundwater recharge, reducing dependence on freshwater sources. Such water reuse opportunities can generate revenue or cost savings, improving the technology's long-term value proposition. Moreover, the smaller volume of sludge generated by MBRs can help reduce disposal costs and environmental impacts. When evaluated holistically, all these factors illustrate that while MBRs may have a higher upfront costs, their overall operational and environmental benefits can lead to improved cost-effectiveness over time.

CONCLUSION

In Indonesia, MBRs are carried out for liquid waste processing. In large cities, such as Jakarta, MBR processing has begun to be developed. However, efforts to improve the performance of MBR membranes are still very low, and research focusing on the modification of MBR membranes is also still very limited.

Membrane modification in MBR requires further study, especially to improve its photocatalytic performance. The reactor configuration also greatly affects the MBRs performance; how the light source illuminates the membrane affects the performance of the photocatalyst.

If the membrane receives only light at the top, the photocatalytic process occurs only on the membrane surface. Thus far, adding photocatalysts to MBR is a promising strategy because it can improve membrane performance.

Several factors that still need to be studied besides increasing photocatalytic activity include pollutant degradation kinetics, membrane-fouling mechanisms, interactions between foulant and the membrane surface, economic factors in developing MBRs on a larger scale, integration of MBRs with other waste treatment routes and challenges in scaling up photocatalytic membrane MBRs

SUPPORTING INFORMATION

There is no supporting information in this review article. The supporting data are available on request from LPH.

ACKNOWLEDGEMENTS

We acknowledged the support from nanocarbon functional research group, National Innovation, and Research Agency, Tangerang Selatan.

CONFLICT OF INTEREST

There was no conflict of interest in this study

AUTHOR CONTRIBUTIONS

LPH contributed to idea development, data management, data curation, analysis, review, writing, and editing.

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