



# A Systematic Literature Review on Agricultural Effluent Treatment using Advanced Membrane Technologies

Tutuk Djoko Kusworo\* and Dani Puji Utomo

Department of Chemical Engineering, Faculty of Engineering, Universitas Diponegoro, Indonesia

Email: [tdkusworo@che.undip.ac.id](mailto:tdkusworo@che.undip.ac.id)

**Abstract** - Agricultural wastewater poses significant environmental challenges due to its complex composition, including high concentrations of nutrients, organic matter, and emerging contaminants. Membrane-based technologies have emerged as advanced solutions for effective treatment and resource recovery from such effluents. This review provides a comparative analysis of various membrane systems—pressure-driven membranes, membrane bioreactors (MBRs), photocatalytic membranes, forward osmosis (FO), membrane distillation (MD), and adsorptive membranes—focusing on their performance in terms of pollutant removal, fouling behavior, energy consumption, and cost-effectiveness. Photocatalytic and FO membranes exhibit high potential for removing persistent organic pollutants and ensuring water reuse, while MD and MBRs demonstrate robust performance in nutrient and organic load reduction. Adsorptive membranes offer selective removal capabilities, particularly for antibiotics and pesticides, although scalability remains a concern. Advances in membrane materials, surface modifications, and hybrid system integration are paving the way for enhanced operational efficiency. The findings underscore the need for integrated, multi-barrier treatment approaches and continued innovation to meet the sustainability requirements of agricultural wastewater management.

**Keywords** - Agricultural wastewater; Advanced membrane technology; Effluent treatment; Photocatalytic membranes; Membrane fouling control

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## 1. Introduction

Agricultural activities are indispensable for global food and economic security, but they also contribute significantly to environmental pollution through the generation of diverse effluents (Rani et al., 2024). These effluents, originating from livestock operations, aquaculture, crop cultivation, and agro-industrial processing (e.g., palm oil mills, natural rubber production, cassava and starch factories), contain a complex mix of contaminants such as nutrients, pesticides, heavy metals, suspended solids, organic matter, and pathogens (Kumar et al., 2024; Kusworo, Kumoro, Aryanti, et al., 2023). When improperly managed, agricultural effluents can severely degrade soil structure, fertility, and microbial balance, leading to reduced crop productivity and disruption of essential ecosystem functions like nutrient cycling and pest control.

In particular, agricultural runoff is a major non-point source of water pollution, transporting excess nitrogen, phosphorus, and agrochemicals into nearby water bodies (Yargholi et al., 2024). This can result in eutrophication, hypoxia, and long-term degradation of surface and groundwater quality (Khalili & Moridi, 2025). For instance,

nutrient over-enrichment due to fertilizer and manure runoff threatens aquatic biodiversity, impairs water usability, and poses risks to public health (Sabina et al., 2025). These issues hinder progress toward several United Nations Sustainable Development Goals (SDGs), especially SDG 6 (Clean water and sanitation), SDG 12 (Responsible consumption and production), and SDG 13 (Climate action).

To mitigate these impacts, agricultural wastewater treatment has become a crucial area of research and innovation. Conventional treatment systems typically comprise (Ahmed et al., 2021):

- Primary treatment: Physical and chemical processes (e.g., sedimentation, coagulation) to remove large solids and prepare effluent for further treatment;
- Secondary treatment: Biological processes such as activated sludge systems or bioreactors that degrade organic pollutants;
- Tertiary treatment: Advanced methods including filtration, adsorption, disinfection, and nutrient polishing to remove residual micropollutants and pathogens.

Beyond conventional approaches, eco-technologies such as microalgae-based systems and constructed wetlands offer sustainable options with high nutrient removal efficiencies (El Bakraoui et al., 2023; Šereš et al., 2021). Microbial fuel cells (MFCs) represent an emerging solution that couples wastewater treatment with renewable electricity generation (Kuleshova et al., 2022). Additionally, advanced oxidation processes (AOPs) and adsorption techniques (e.g., using activated carbon, biochar, chitosan) are increasingly integrated into hybrid systems for treating persistent and recalcitrant pollutants (Gahrouei et al., 2024).

Among these solutions, Membrane technologies are increasingly recognized as essential tools for wastewater treatment due to their high efficiency, operational flexibility, and environmental sustainability (Kusworo, et al., 2023). These technologies enable precise separation of contaminants and are adaptable to various water matrices, including complex agricultural effluents. Different membrane processes offer tailored solutions based on the nature and size of the pollutants:

- Microfiltration (MF): Primarily used to remove suspended solids, bacteria, and some viruses from wastewater (Kuleshova et al., 2022).
- Ultrafiltration (UF): Effective for eliminating larger organic molecules, colloids, and pathogens (Fatima et al., 2021).
- Nanofiltration (NF): Suitable for separating multivalent ions, organic compounds, and certain micropollutants (Mkilima et al., 2022).
- Reverse Osmosis (RO): Widely used for desalination and the removal of dissolved salts and a broad spectrum of organic contaminants (El Sayed et al., 2022).
- Forward Osmosis (FO): An emerging, energy-efficient technique for concentrating wastewater and promoting water reuse, offering lower energy demands and potential for high recovery rates compared to RO (Almansouri et al., 2024).
- Membrane Bioreactors (MBRs): Integrate biological degradation with membrane filtration, offering compact and efficient treatment for municipal and industrial effluents (Gadkari, 2021).
- Photocatalytic Membranes: Advanced membranes embedded with nanomaterials, such as titanium dioxide (TiO<sub>2</sub>), that enable simultaneous filtration and degradation of persistent pollutants through photocatalytic activity (Z. Wang et al., 2022).

These membrane systems are particularly well-suited for treating agricultural wastewater, which often contains elevated concentrations of nutrients (nitrogen and phosphorus), pesticides, antibiotics, and organic matter (Kamalesh et al., 2024). Their ability to deliver high-quality effluent with reduced chemical usage and minimal environmental footprint makes them a promising component of sustainable agricultural water management.

Despite their advantages, membrane systems face challenges such as fouling, concentrate management, and energy demands, which can limit their cost-effectiveness

and operational lifespan (AlSawaftah et al., 2021). Recent research focuses on membrane modification, pre-treatment strategies, and hybrid system development to address these limitations and improve long-term sustainability.

Given the increasing relevance of agricultural wastewater management and the rapid advancement of membrane technology, this review aims to provide a systematic assessment of membrane-based technologies for agricultural effluent treatment. The specific objectives are to:

- Identify and classify the types and sources of agricultural effluents and their environmental implications;
- Summarize the performance, advantages, and limitations of membrane technologies (MF, UF, NF, RO, FO, MBR, and photocatalytic membranes) applied to agricultural wastewater;
- Highlight operational considerations and fouling mitigation strategies for improving treatment efficiency and membrane longevity;
- Evaluate the potential of membrane systems for effluent reuse, resource recovery, and contribution to sustainable agriculture.

The novelty of this review lies in its sector-specific focus on agricultural effluents—an area less explored in the broader context of membrane technology applications. It consolidates the latest developments in nanomaterial-enhanced membranes, hybrid treatment systems, and reuse strategies, offering a timely, targeted synthesis that aligns with global goals for sustainable water and agricultural resource management.

## 2. Materials and Methods

A systematic literature search was conducted using the Scopus database, a reputable international source of peer-reviewed scientific publications. The objective was to identify studies focusing on the treatment of agricultural wastewater using advanced membrane technologies. The search strategy employed a combination of keywords related to both wastewater sources and membrane-based treatment methods. The source-related keywords included “Agricultural,” “Agriculture,” “Farm,” “Poultry,” “Dairy,” and “Harvest,” while wastewater-related terms included “Wastewater,” “Effluent,” “Runoff,” “Liquid waste,” and “Liquid residue.” For the membrane technologies, the keywords used were “Hybrid membrane,” “Photocatalytic membrane,” “Adsorptive membrane,” “Membrane distillation,” “Membrane bioreactor,” “Nanocomposite membrane,” “Combined treatment membrane,” “AOPs membrane,” and “Fenton membrane.” Boolean operators (AND, OR) were used to combine these terms to refine the search.

The search was limited to publications from the last 15 years, specifically from 2010 to 2025, and filtered to include only original research articles, review articles, and conference papers. This initial search yielded a total of 298 articles. The inclusion criteria required that articles focus on

agricultural wastewater treatment using membrane-based technologies. Exclusion criteria eliminated materials such as books, presentations, letters to the editor, and studies unrelated to the specified topic.

The search results were exported in BibTeX format and imported into the Rayyan AI screening tool. Duplicate entries were removed automatically. Two independent reviewers then screened the remaining articles by examining their titles, abstracts, and full texts to ensure relevance to the research focus. Articles that did not meet the inclusion criteria were excluded. From the initial 298 documents, 186 articles were excluded based on the stated criteria, resulting in 112 articles that were included in the final review.

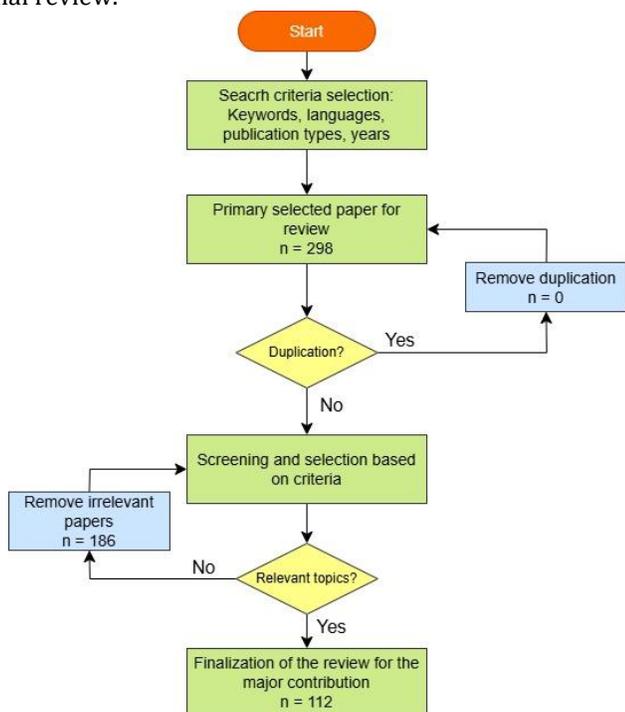


Figure 1. Flowchart depicting the stages of article screening and selection

Key information was extracted from each selected study, including the title, authors, journal name, publication year, membrane type, wastewater type, effects of operational parameters, removal efficiency, treatment mechanisms, and optimal treatment conditions. The overall screening and selection process is summarized in a flow diagram (Figure 1), illustrating each step taken to ensure the systematic identification of relevant literature.

### 3. Characteristics of Agricultural Effluents

Wastewater generated from agricultural sectors varies significantly in composition depending on the source and activity, but it typically contains a mix of organic matter, nutrients, suspended solids, and chemical contaminants as shown in Table 1. Livestock and poultry farming effluents exhibit high levels of BOD (1070–1821 mg/L), COD (2350–7719 mg/L), and nutrients such as nitrogen and phosphorus, along with pathogens and antibiotics, making treatment both essential and challenging. Similarly, dairy farming wastewater is rich in organic matter, fats (up to 1334 mg/L), and suspended solids, with BOD and COD levels ranging from 798–4520 mg/L and 1945–6280 mg/L, respectively. Aquaculture wastewater, while less concentrated in organic pollutants, contains significant nitrogen (up to 1000 mg/L), phosphorus (~52 mg/L), and traces of antibiotics, which can affect surrounding ecosystems.

On the other hand, wastewater from crop farming and horticulture is typically lower in organic content but often carries nutrient residues (TN up to 75.8 mg/L) and pesticides due to runoff from fertilizers and agrochemicals. Meat processing wastewater is among the most concentrated, with COD reaching 14,160 mg/L and TN up to 519 mg/L, alongside a significant pathogen load, requiring rigorous treatment. Lastly, agro-industrial effluents—such as those from natural rubber and palm oil processing—contain extremely high COD levels (up to 18,479 mg/L), substantial nutrient loads (TN up to 2228 mg/L), and may also include heavy metals, emphasizing the necessity for targeted, advanced treatment approaches.

Table 1. Characteristics of various sectors in agricultural activities

Sectors	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	Others
Livestock and Poultry	6.5 – 8.0 <sup>a,b</sup>	1070 – 1821 <sup>b,c</sup>	2350 – 7719 <sup>b,c</sup>	378 – 5462 <sup>c,d</sup>	162 – 563 <sup>b,c</sup>	7.05 – 62.86 <sup>b,c</sup>	Antibiotics Pathogens <sup>e</sup>
Dairy farming	5.9 – 9.2 <sup>f</sup>	798 – 4520 <sup>f,g</sup>	1945 – 6280 <sup>f,g</sup>	181 – 1537 <sup>f,g</sup>	33 – 179 <sup>f</sup>	18 – 101 <sup>f</sup>	Fats (45 – 1334 mg/L) <sup>f</sup> Antibiotics
Aquaculture	~7 <sup>h</sup>	~814 <sup>i</sup>	~2289 <sup>j</sup>		17.53 – 1000 <sup>k</sup>	~52 <sup>k</sup>	Antibiotics
Crop farming	3.5 – 6.8 <sup>l</sup>	90 – 130 <sup>m</sup>	200 – 300 <sup>m</sup>	200 – 600 <sup>m</sup>	~75.8 <sup>n</sup>	~8.5 – 18.1 <sup>n</sup>	Pesticides <sup>n</sup>
Horticulture	~7.22 <sup>o</sup>	41.2 – 1674 <sup>o,p</sup>	86.6 – 8064 <sup>o,p</sup>	~1540 <sup>p</sup>	22.4 <sup>o</sup>	2.2 – 18.1 <sup>n,o</sup>	Pesticides <sup>o</sup>
Meat processing	6.5 – 8.0 <sup>b</sup>	1070 – 6960 <sup>q,r</sup>	2350 – 14160 <sup>q,r</sup>	~1400 <sup>b</sup>	317 – 519 <sup>s</sup>	~62.86 <sup>b</sup>	Pathogens <sup>t</sup>

Sectors	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	Others
Agro-industrial	6.3 – 6.8 <sup>u</sup>	234 – 1440 <sup>v</sup>	567 – 18479 <sup>v</sup>	554 – 686 <sup>v</sup>	205 – 2228 <sup>v</sup>	8.5 – 306 <sup>v</sup>	Heavy metals <sup>w</sup>

References: <sup>a</sup>(D. Chen et al., 2020); <sup>b</sup>(Latiffi et al., 2019); <sup>c</sup>(Yaakob et al., 2018); <sup>d</sup>(Meiramkulova et al., 2020); <sup>e</sup>(Sharma et al., 2023); <sup>f</sup>(Flayyih & Ali, 2023); <sup>g</sup>(Nabbou et al., 2020); <sup>h</sup>(Mohamad et al., 2017); <sup>i</sup>(Singh et al., 2024); <sup>j</sup>(Karia et al., 2022); <sup>k</sup>(Tang et al., 2021); <sup>l</sup>(Gebrehanna et al., 2014); <sup>m</sup>(Khan et al., 2019); <sup>n</sup>(N'Diaye et al., 2013); <sup>o</sup>(Dehghani et al., 2018); <sup>p</sup>(Aarfane et al., 2025); <sup>q</sup>(León-Becerril et al., 2016), <sup>r</sup>(Milanović et al., 2016), <sup>s</sup>(Rouland et al., 2024), <sup>t</sup>(Makara et al., 2025); <sup>u</sup>(Amor et al., 2019); <sup>v</sup>(R. Liu et al., 2016); <sup>w</sup>(Khurana & Singh, 2012)

Given the highly variable characteristics of agricultural wastewater, as previously discussed, wastewater treatment plants often encounter significant challenges in maintaining stable operational conditions. Variability in influent flow rates, organic loading, and pollutant concentrations—especially from sectors like livestock farming, dairy processing, and agro-industrial activities—can cause upsets in biological treatment units such as the Activated Sludge Process (ASP) (Leu et al., 2012). To mitigate these fluctuations, the use of equalization tanks is strongly recommended, as they buffer hydraulic and organic shock loads, thus promoting stable performance in downstream biological systems.

Moreover, membrane-based treatment systems, increasingly employed for their high pollutant removal efficiency, face persistent challenges related to membrane fouling (Shehata et al., 2023). This issue is aggravated under conditions common in agricultural wastewater, such as elevated concentrations of dissolved organic carbon (DOC) and extracellular polymeric substances (EPS), as well as fluctuating flow rates and low temperatures (AbuKhadra et al., 2024). Fouling not only reduces membrane permeability and lifespan but also increases operational costs due to more frequent cleaning and maintenance. Considering of costs, the operation of wastewater treatment systems involves substantial expenditures in energy, labor, maintenance, and chemical reagents. Energy consumption is particularly significant in aeration-intensive processes like ASP, often accounting for the largest share of the total operating budget (Badeti et al., 2022). Therefore, addressing variability and fouling through proper pre-treatment, process control, and energy-efficient technologies is essential for enhancing the reliability and sustainability of agricultural wastewater treatment systems.

#### 4. Advanced Membrane Technologies for Treatment

Advanced membrane technologies are gaining prominence in the treatment of agricultural wastewater due to their high efficiency in removing a broad spectrum of contaminants, including organic matter, nutrients, suspended solids, pathogens, and emerging pollutants. Technologies such as pressure-driven membranes (e.g., MF, UF, NF, RO), membrane bioreactors (MBRs), photocatalytic membranes, hybrid membrane systems, and forward osmosis (FO) are being actively developed and applied to address the growing complexity of agricultural effluents. These systems are designed not only to enhance contaminant removal but also to address key challenges such as membrane fouling, high energy consumption, and the need for process integration and operational optimization. Continuous innovation in membrane materials, configurations, and combined treatment approaches is critical for improving system resilience, sustainability, and applicability in diverse agricultural settings.

##### 4.1. Pressure-driven Membranes

Pressure-driven membrane technologies—such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—have gained increasing attention for their effectiveness in treating wastewater from agricultural sectors. These technologies are particularly suitable for managing the complex composition of agricultural effluents, which typically contain a mixture of organic matter, nutrients, suspended solids, pathogens, and inorganic pollutants (Cartwright, 2012; Kumar et al., 2024). Figure 2 illustrate the separation mechanism of pressure-driven membranes. Among these, UF and NF membranes have demonstrated high removal efficiencies for nitrogen, phosphorus, and various organic contaminants, making them suitable for treating runoff from livestock, poultry, aquaculture, and crop production (Dagar et al., 2023; Ho & Isma, 2023).

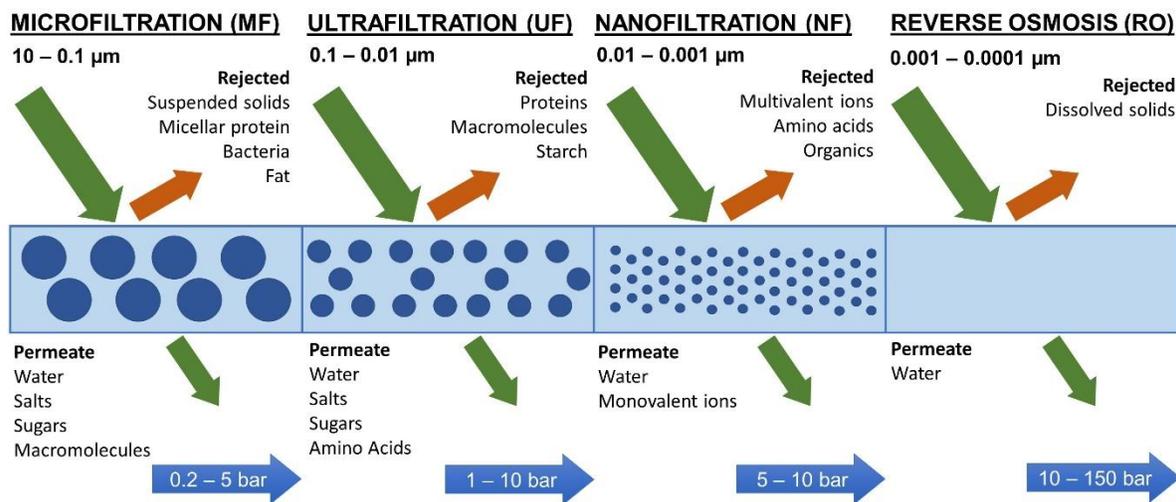


Figure 2. Mechanism of pressure-driven membrane in removing pollutants

Numerous studies have reported the performance of UF membranes in agricultural wastewater applications. For instance, UF membranes combined with coagulation have achieved up to 97% COD removal (Zielińska & Galik, 2017), while standalone UF membranes were reported to remove up to 94% COD in poultry wastewater (Malmali et al., 2018). Additionally, TSS removal rates reached 99.9%, and pathogen removal was reported to be as high as 99.99% (Dada et al., 2023). In dairy wastewater treatment, the combination of UF and NF membranes enabled 94-97% recovery of proteins and complete (100%) lactose recovery (Chen et al., 2017). Similarly, UF-RO combinations have been effective in meat processing wastewater, achieving over 99% removal efficiencies for COD and BOD (Meiramkulova et al., 2020).

Reverse osmosis (RO) membranes are particularly effective in removing dissolved solids, with reported removal efficiencies of up to 96.1% for total dissolved solids (TDS) (Salgado-Reyna et al., 2015). Nanofiltration membranes also exhibit notable performance in removing heavy metals, with studies indicating over 90% removal efficiency in both synthetic and real industrial effluents (Efligenir et al., 2014). The integration of different membrane types—such as UF followed by RO—has been shown to significantly enhance treatment performance. For example, a study reported an increase in COD removal from 70% to 88.67% when combining UF with RO (Özdemir et al., 2021).

Despite their effectiveness, one of the primary operational challenges associated with pressure-driven membrane processes is membrane fouling, which reduces permeability and long-term performance. Fouling is influenced by factors such as high organic load, suspended solids, EPS, and operating conditions including low temperature and high transmembrane pressure (Kertész et al., 2014). To mitigate fouling and improve membrane lifespan, pre-treatment methods such as coagulation, electrocoagulation, and ozonation are commonly employed

(Barbieri et al., 2021; Kusworo et al., 2021). Moreover, optimization of operational parameters—such as pressure, flux, and cleaning frequency—is essential to maintaining system efficiency and sustainability in agricultural wastewater treatment.

#### 4.2. Membrane Bioreactors (MBRs)

Membrane bioreactors (MBRs) are advanced treatment systems that integrate conventional biological processes with membrane filtration, offering a compact and efficient solution for wastewater treatment. The core of the MBR system lies in the activated sludge process, where microorganisms degrade organic pollutants, and the subsequent membrane filtration stage, typically using microfiltration (MF) or ultrafiltration (UF) membranes, serves as a physical barrier to separate solids and pathogens as illustrated in Figure 3. Operating with higher biomass concentrations than traditional systems, MBRs enhance the degradation of organic matter while reducing sludge production and producing high-quality effluent suitable for water reuse applications. Due to their compact footprint and operational flexibility, MBRs are especially well-suited for sites with limited space and varying influent characteristics, including those from municipal, industrial, and agricultural sources.

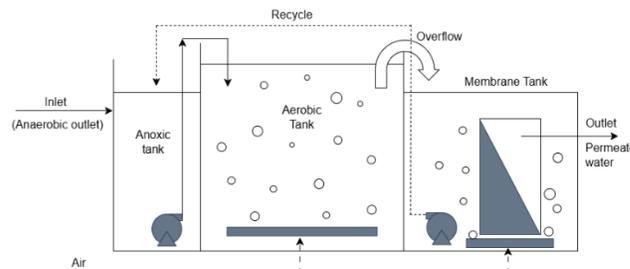


Figure 2. Typical illustration of aerobic submerged membrane bioreactor (sMBR)

In the context of agricultural wastewater, MBRs have demonstrated high removal efficiencies for a broad range of contaminants, including organic matter (COD, BOD),

nutrients (nitrogen, phosphorus), pathogens, and emerging pollutants such as pesticides, herbicides, and endocrine-disrupting compounds. For instance, hybrid MBRs (HMBRs) have reported COD removal efficiencies of 90–95.7% (Vaezi et al., 2025), while immersed MBRs (iMBRs) have shown COD removal ranging from 55.7% to 95.5% and BOD removal from 75.7% to 98.6% (Chhillar et al., 2020). An aerobic submerged MBR (sMBR) achieved removal rates of 98.2% for COD, 95.4% for ammonia-nitrogen, and 88.9% for orthophosphate (Paçal & Semerci, 2023). Anaerobic configurations, such as anaerobic dynamic membrane bioreactors (AnDMBRs) and anaerobic MBRs (AnMBRs), have also been effective, with COD removal efficiencies between 85–95% and the added benefit of methane generation (0.13–0.18 L CH<sub>4</sub>/g COD removed), highlighting their potential for energy recovery (Galib et al., 2016).

Hybrid configurations and integrated systems have further enhanced MBR performance. A hybrid MBR–RO system achieved COD removal efficiencies of 92–95% (Abyar & Nowrouzi, 2020), while coupling AnMBR with constructed wetlands (CWs) has yielded over 90% removal of ammonium and phosphorus (de Oliveira Demarco et al., 2025). MBRs have also been integrated into poultryponics systems, resulting in *Salmonella* reductions of 99.6% in algal bioreactors and 97.5% in bacterial systems (Arthur et al., 2025). Additionally, a two-stage aerobic treatment for poultry manure wastewater achieved 99.5% ammonia-nitrogen removal and 75% COD reduction (Li et al., 2016), and a hydrogen-based autotrophic denitrification system coupled with an MBR showed over 90% nitrate removal (Dong et al., 2021).

Despite their advantages, membrane fouling remains the most significant limitation in MBR operation. Fouling is typically caused by colloidal deposition, organic adsorption, scaling, and biofouling (Amiraftebi et al., 2014), all of which reduce membrane permeability and operational efficiency. A range of fouling control strategies has been investigated, including physical and chemical cleaning, aeration optimization, and membrane surface modification (Liu et al., 2021). Innovative techniques such as air-jet injection and the use of nanospheres have also shown promise in mitigating fouling (Shehata et al., 2023). Furthermore, MBR systems are energy-intensive, particularly due to the requirements of aeration and membrane filtration. Electricity consumption represents a major share of the operational cost and environmental footprint of MBR systems (Andersson et al., 2024; Hospido et al., 2012). Therefore, current research continues to focus on enhancing energy efficiency, reducing fouling, and optimizing integrated configurations to improve the sustainability and cost-effectiveness of MBRs for agricultural wastewater treatment.

### 4.3. Photocatalytic Membranes and Hybrid Systems

Photocatalytic membranes represent a promising hybrid technology that integrates photocatalysis and membrane filtration to enhance the treatment of complex

wastewater, including that generated from agricultural sources. This dual-function system combines the oxidative degradation of pollutants with physical separation, offering a synergistic approach to removing a wide spectrum of contaminants. The mechanism as shown in Figure 4 involves two main processes: under light irradiation, photocatalysts such as TiO<sub>2</sub>, ZnO, or BiVO<sub>4</sub> generate reactive oxygen species (e.g., hydroxyl radicals) that degrade organic pollutants into less harmful or inorganic end-products; simultaneously, the membrane filtration process retains particulate matter and microorganisms, enabling the separation of treated water (Kusworo et al., 2022). Notably, the photocatalytic activity contributes to fouling mitigation, extending membrane lifespan and improving long-term operational performance.

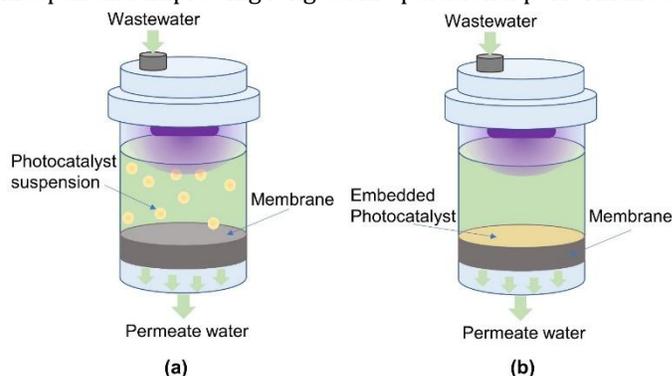


Figure 4. Photocatalytic membrane configuration in dead-end cell (a) suspended photocatalyst, (b) embedded photocatalyst in membrane matrix

Recent advancements in photocatalytic membrane materials have significantly enhanced treatment efficiency, antifouling behavior, and pollutant removal rates. Incorporation of nanoparticles such as TiO<sub>2</sub>, carbon nanotubes, and BiVO<sub>4</sub> into polymeric membranes has improved flux performance, recovery ratios, and stability under varied conditions. For example, Sisay et al. (2023) demonstrated that such composite membranes effectively treated dairy wastewater, although performance was sensitive to factors like salinity, pH, and lactose concentration. Subramaniam et al. (2021) reported that boron-doped titania nanotube (TNT) layers immobilized on a PVDF hollow fiber membrane achieved a maximum flux of 39.62 L/m<sup>2</sup>·h and 79.42% color removal, with more than 95% flux recovery over four filtration cycles, indicating strong antifouling potential for agricultural wastewater treatment. The photocatalytic membrane also provides antifouling and self-cleaning features as reported by previous study (Kusworo, Yulfarida, Kumoro, et al., 2023).

Innovative reactor configurations are also being explored. The Photocatalytic Nanofiltration Reactor (PNFR) is a notable example, which achieves synergistic enhancement through combined photocatalytic degradation and membrane rejection. Theodorakopoulos et al. (2023) demonstrated that the PNFR system could effectively remove pesticides such as Acetamiprid (ACT) and Thiabendazole (TBZ) from real agro-wastewater, while operating at low pressures and achieving a recovery rate of

15 m<sup>3</sup>/day, highlighting its practical viability. Additionally, Wang et al. (2022) reported the self-assembly of 2D MOF-2/g-C<sub>3</sub>N<sub>4</sub> nanosheets into membranes that exhibited outstanding removal efficiencies—98% for atrazine (ATZ), 95% for tetracycline (TC), 89% for sulfamethazine (SMT), and 92% for sulfamethoxazole (SMX). The removal mechanism was attributed to pollutant enrichment, enhanced photocatalytic degradation, and electrostatic repulsion of by-products. Similarly, a biochar@NiFe<sub>2</sub>O<sub>4</sub> (BC@NiFe<sub>2</sub>O<sub>4</sub>) nanocomposite showed high photocatalytic degradation of agricultural pesticides (98% for acetamiprid and 92% for esfenvalerate), with excellent reusability up to eight cycles (M. Rani et al., 2024), indicating strong potential for sustainable application.

Despite these promising laboratory-scale outcomes, several challenges remain for large-scale deployment. Issues related to catalyst recovery, membrane durability, and cost-effectiveness need to be addressed. Moreover, operational parameters such as pH, light source type, catalyst concentration, and the presence of oxidants significantly influence the efficiency of photocatalytic processes and must be carefully optimized for real-world agricultural wastewater treatment. Continued research on material innovation, reactor design, and process integration will be critical to advancing photocatalytic membrane technologies toward full-scale, sustainable applications in the agricultural sector.

#### 4.4. Forward Osmosis (FO) and Emerging Membranes

Forward osmosis (FO) is an emerging membrane separation technology that utilizes the natural osmotic pressure gradient between a feed solution and a concentrated draw solution to drive water transport through a semi-permeable membrane (Figure 5). Unlike pressure-driven systems such as reverse osmosis (RO), FO operates at low or no hydraulic pressure, making it more energy-efficient. FO has demonstrated high potential for treating various wastewater streams, particularly in removing organic pollutants. For instance, FO has been reported to achieve over 95% removal of organic contaminants from municipal wastewater treatment plant (WWTP) effluents, effectively reducing toxicity and bacterial concentrations (Escolà Casas et al., 2024). Applications in aquaculture wastewater treatment have also shown promise, with optimized operational parameters—such as draw solution concentration, cross-flow velocity, and temperature—significantly improving water flux and organic matter rejection (Cheng et al., 2022). Furthermore, the fertilizer-drawn forward osmosis (FDFO) process has enabled simultaneous water reuse and nutrient recovery for hydroponic applications, with 95% water recovery identified as an optimal condition for subsequent anaerobic MBR (AnMBR) treatment (Chekli et al., 2017). However, challenges remain in FO implementation, including membrane fouling and internal concentration polarization (ICP), which reduce effective osmotic gradients and water flux (Almansouri et al., 2024). Back diffusion of draw solutes

into the feed solution also poses a concern, potentially compromising the quality of the treated water.

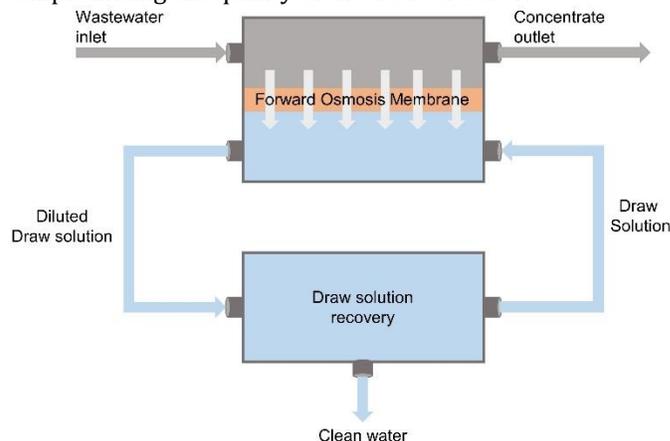


Figure 5. Process mechanism of forward osmosis (FO)

In addition to FO, other emerging membrane technologies, such as membrane distillation (MD) and adsorptive membranes, have gained attention for treating agricultural, poultry, meat processing, and dairy wastewater. MD is a thermally driven process employing hydrophobic membranes to facilitate water vapor transport while rejecting dissolved solutes. This method has demonstrated high removal efficiencies for COD and total phosphorus (up to 99%) in digestate from livestock wastewater (Kim et al., 2016), and can recover valuable nutrients and high-quality water from dairy effluents at relatively low energy input (Wang et al., 2020). MD integrated with anaerobic osmotic membrane bioreactors (AnOMBRs) or thermophilic MBRs has achieved nearly complete removal of nutrients and trace organic contaminants (TrOCs), indicating its effectiveness for post-treatment polishing (Chang et al., 2019; Wijekoon et al., 2014). However, membrane fouling and wetting—particularly when treating organic- and nutrient-rich wastewater—remain significant operational challenges. Pre-treatment methods and membrane modifications, as well as integrating MD with loose nanofiltration (LNF), have been proposed to reduce fouling and enhance system performance (Laqbaqbi et al., 2025; Liu et al., 2023).

Adsorptive membranes represent another promising technology for agricultural wastewater treatment, particularly for targeting nutrients, volatile organic compounds (VOCs), and emerging contaminants. These membranes, often functionalized or embedded with adsorbents like crop residue-derived activated carbon, have achieved removal efficiencies exceeding 95% for VOCs and demonstrated high desalination performance (Rathore et al., 2025). Despite their efficacy, membrane fouling and limited adsorption capacity pose practical limitations. Recent research has focused on enhancing antifouling properties and developing scalable, low-cost materials to support large-scale implementation (Fadila et al., 2022; Rani et al., 2025). Additionally, more investigation is needed on the effectiveness of adsorptive membranes in removing

emerging contaminants such as antibiotics and pesticides, which are prevalent in agricultural runoff and livestock effluents.

Membrane technologies have become indispensable in advanced wastewater treatment, particularly for addressing the complex and variable composition of agricultural and industrial effluents. A variety of membrane-based systems have been developed, each offering distinct performance characteristics, benefits, and limitations.

### 5. Comparative Analysis and Discussion

Table 2. Comparative Analysis of Various Advanced Membrane Processes

Aspect	Pressure-Driven Membranes	Membrane Bioreactors (MBRs)	Photocatalytic Membranes	Forward Osmosis (FO)	Membrane Distillation (MD)	Adsorptive Membranes
Removal Rates	High (salts, organics, TDS)	High (organics, pathogens)	Very high (persistent organics, antibiotics)	High (organics, nutrients)	Very high (COD, salts, nutrients)	High (targeted pollutants like VOCs, pesticides)
Fouling Potential	High (biofouling, scaling)	Moderate-High (biofouling)	Low-Moderate (photodegradation reduces fouling)	Moderate (concentration polarization)	High (organic fouling, wetting)	Moderate-High (adsorbent saturation)
Energy Efficiency	Low-Moderate (RO is high)	Moderate (high for aeration)	Moderate (depends on light source)	High (no high-pressure pump needed)	Moderate-Low (uses thermal energy)	High (passive or low-energy operation)
Operational Cost	High (cleaning, maintenance)	Moderate-High	Moderate (catalyst cost, cleaning)	Low-Moderate (draw solute recovery adds cost)	Moderate (heating requirement)	Low-Moderate (low-cost materials, some need regeneration)
Strengths	Proven, widely used, modular	Excellent biodegradation, robust	Dual function (degradation + separation), antifouling	Low energy use, high selectivity	High rejection, can use waste heat	Targeted removal, renewable materials
Limitations	Prone to fouling, pressure demand	Fouling, energy for aeration	Light dependency, material stability, scale-up challenges	Draw solute recovery, CP, reverse solute flux	Fouling and wetting under high organics	Fouling from saturation, limited large-scale data
Key Innovations	Nanomaterials, anti-scaling coatings	Granular sludge, surface modification	MOFs, 2D materials, visible-light catalysts	Improved draw solutes, hybrid FO-AnMBR	Hydrophobic coating, hybrid AnOMBR	Biochar-based adsorbents, photothermal membranes

Pressure-driven membranes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), are among the most widely adopted technologies. They are effective in removing suspended solids, pathogens, and dissolved salts, depending on the membrane pore size. However, these systems are highly prone to fouling—especially from organic matter, biofilms, and scaling—which necessitates frequent cleaning,

membrane replacement, and pretreatment, thereby increasing operational costs. Energy consumption varies by membrane type, with RO requiring the highest pressure and thus the most energy. Despite their maturity and commercial availability, pressure-driven systems often face limitations in long-term economic sustainability.

Membrane bioreactors (MBRs) combine biological degradation with membrane separation, enabling efficient

removal of biodegradable organics and ammonia while producing high-quality effluent. MBRs are particularly robust under fluctuating influent conditions, making them suitable for agro-industrial and municipal applications. However, challenges remain in terms of biofouling, membrane clogging, and high energy consumption—especially from aeration processes. Recent advancements have focused on fouling control through granular sludge systems, dynamic aeration strategies, and surface-engineered membranes to extend membrane lifespan and reduce energy use.

Photocatalytic membranes represent a hybrid approach that integrates photocatalysis with membrane filtration, enabling both degradation of recalcitrant organics and physical separation. These systems exhibit high efficiency in removing antibiotics, pesticides, and other persistent pollutants, while mitigating membrane fouling due to the oxidative cleaning action of photocatalysts such as  $\text{TiO}_2$ ,  $\text{BiVO}_4$ , and MOF-based nanocomposites. Nonetheless, their performance is sensitive to environmental variables such as light intensity, pH, and catalyst loading. Moreover, the scalability and long-term stability of these systems remain under investigation.

Forward osmosis (FO) employs osmotic pressure gradients to drive water flux from a low-concentration feed solution into a high-concentration draw solution. FO systems demonstrate low energy requirements and high rejection of organic pollutants, making them attractive for agricultural wastewater treatment and water reuse. However, performance is limited by internal and external concentration polarization, membrane fouling, and reverse solute diffusion. Recovery and regeneration of draw solutions also present economic and technical challenges, despite the potential for nutrient recovery and integration into circular water systems.

Membrane distillation (MD) is a thermally driven separation technique that utilizes hydrophobic membranes to extract water vapor while rejecting non-volatile solutes. MD systems achieve near-complete removal of salts, nutrients, and organic pollutants and are particularly suited for high-strength wastewater when low-grade or waste heat is available. Key limitations include membrane wetting, fouling from surfactants and organic matter, and relatively low flux compared to pressure-driven membranes. Ongoing research in surface modification, feed pretreatment, and hybridization with anaerobic or nanofiltration systems aims to enhance MD's viability and operational robustness.

Adsorptive membranes, which integrate sorbent materials such as activated carbon, biochar, or metal-organic frameworks into membrane structures, offer targeted removal of pollutants including heavy metals, antibiotics, and volatile organics. These membranes exhibit high selectivity and are particularly effective for nutrient-rich agricultural wastewaters. However, they often suffer from saturation, reduced adsorption capacity over time, and fouling from complex feed matrices. Regeneration techniques and the development of low-cost sorbent

materials have improved their sustainability and scalability, although commercial deployment is still emerging.

Across all membrane platforms, key innovations are converging around fouling mitigation, membrane surface modification, and the development of smart membranes. Techniques such as hydrophilic coatings, nanoparticle incorporation, and stimuli-responsive materials are being employed to enhance flux, durability, and self-cleaning properties. Ultimately, no single membrane technology offers a complete solution to the diverse challenges of agricultural and industrial wastewater treatment. Therefore, hybrid membrane systems—which strategically combine complementary mechanisms (e.g., biological degradation, adsorption, photocatalysis, and thermal separation)—represent a promising direction for achieving sustainable, high-performance wastewater treatment.

## 6. Conclusion

This review highlights the diverse membrane technologies currently applied to agricultural wastewater treatment, including pressure-driven membranes, membrane bioreactors (MBRs), photocatalytic membranes, forward osmosis (FO), membrane distillation (MD), and adsorptive membranes. Each system demonstrates distinct advantages in pollutant removal efficiency, energy consumption, and fouling behavior. Pressure-driven membranes offer well-established contaminant removal but are limited by fouling and high maintenance costs. MBRs and MD show strong performance in organic and nutrient removal but demand high energy input. FO and photocatalytic membranes present low-energy alternatives with excellent potential for treating recalcitrant pollutants, while adsorptive membranes provide targeted removal for specific contaminants such as heavy metals and antibiotics. Membrane technology holds substantial promise for managing agricultural effluents, which are typically rich in nutrients, organics, and emerging contaminants. Innovations such as surface modifications, incorporation of nanomaterials, and hybrid systems are actively advancing membrane performance and operational sustainability. Looking forward, future research should prioritize the development of integrated treatment strategies that combine the strengths of multiple membrane processes with biological, chemical, or adsorption-based pre-treatments. Emphasis should also be placed on reducing membrane fouling, improving energy efficiency, and enhancing cost-effectiveness to ensure large-scale, sustainable adoption in agricultural settings.

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