Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat
Volume 23, Nomor 1, Februari 2026
1819-796X (p-ISSN); 2541-1713 (e-ISSN)
https://ppjp.ulm.ac.id/journal/index.php/f *Review Article*

Structure–Property Relationship of Membrane Materials in Water Treatment: Insights from Recent Literature

Nurul Fajri R. Tang[1*], Andi Tessiwoja Tenri Ola[2], Rosdiana Yoku[1], Chrisaria Palungan[3], Dahlia Gladiola R. Manufandu[3], Vita Meylani[4], Rafsanjany Ramadan[5], Ryan Munandar[5]

[1]Departemen Fisika, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Papua, Indonesia
[2]Departemen Fisika, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Lambung Mangkurat, Indonesia
[3]Departemen Matematika dan statistika, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Papua, Indonesia
[4]Departemen Biologi, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Papua, Indonesia
[5]Departemen Kimia, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Papua, Indonesia

Email korespondensi : n.tang@unipa.ac.id

DOI: https://doi.org/10.20527/flux.v23i1.23539

Submitted: 01 August 2025; Revised: 24 November 2025**;** Accepted: 30 November 2025

ABSTRACT

The escalating global clean water crisis, driven by pollution and limited freshwater resources, has intensified the need for efficient and sustainable water treatment technologies. This review critically examines the structure–property relationships of membrane materials and their implications for water purification performance. Comparative analysis of recent studies reveals that hydrophilic membranes with controlled pore size (typically 0.01–0.1 μm) exhibit superior water flux (up to 65 L/m²·h·bar), higher pollutant rejection (>90%), and better fouling resistance than hydrophobic counterparts. Modifications involving nanoparticles (e.g., TiO_2, Fe_3O_4), composites (PES–DLC, PVDF–MOF), and biosurfactants have been shown to enhance hydrophilicity, optimize pore distribution, and extend operational stability. The review highlights the trade-off between permeability and selectivity, emphasizing the critical roles of pore size, contact angle, and surface chemistry in balancing efficiency and durability. It concludes that future membrane development should integrate nanostructure engineering, eco-friendly materials, and data-driven optimization to achieve adaptive, high-performance membranes for sustainable water purification.

KEYWORDS: Structure–roperty relationship; Hydrophilicity; Membrane technology; Nanocomposites; Water treatment

INTRODUCTION

The existence of life on our planet is intrinsically linked to the presence of water. It is the only planet that can be synonymous with "the planet of life." Although approximately 75% of the Earth's surface is covered by water, most of it is found in oceans, lakes, rivers, glaciers, and aquifers. However, 97% of this water is unsuitable for drinking or irrigation because it is saline. Of the remaining 3%, 2.3% is frozen in polar regions and glaciers. Only 0.7% is available for human consumption, most of which is found as groundwater (0.66%), and < 0.03% is found in lakes and rivers as freshwater (Tripathy, 2024). Thus, only a small fraction—less than 1%—is suitable for human consumption. However, rapid population growth, industrial expansion, urbanization, and climate change have led to a decrease in the availability and quality of freshwater resources. Human activities have caused pollution of aquatic environments by various hazardous pollutants such as heavy metals, pharmaceutical waste, cosmetics, synthetic dyes, microplastics, and pathogenic microorganisms, rendering many natural water sources unsafe for use.

According to reports from the World

Health Organization (WHO), the World Bank Group, and UNICEF, approximately 2 billion people in more than 50 countries still lack adeaccess to safe drinking water (Sharma et al., 2023). Water is an essential element for the survival, growth, and reproduction of all living beings. However, the clean water crisis remains a serious global issue. Other data indicate that approximately 663 million people worldwide still lack access to clean and safe drinking water. This situation has fatal consequences, with approximately 2.2 million deaths reported annually due to the consumption of contaminated water and poor sanitation practices. Diseases transmitted through contaminated water, such as acute diarrhea, have become a leading cause of death, especially among children; it is even reported that every 8 seconds, one child loses their life due to water-related illnesses (Shahid et al., 2024). Additionally, a 2021 report noted more than 251.4 million cases of schistosomiasis, a chronic disease caused by parasitic infection through direct contact with contaminated water. These facts underscore the crucial role of clean water availability in human health and survival.

With the shrinking of clean water resources, water pollution has become an increasingly urgent environmental challenge. Various conventional methods, such as chemical oxidation, photocatalysis, sonocatalysis, microbial treatment, ozonation, reverse osmosis, coagulation, electrolysis, and adsorption, have been developed to treat waste and prevent contamination. However, although effective under certain conditions, these methods often face various limitations, such as complex processes, high energy requirements, dependence on chemicals, the formation of secondary sludge, and low effectiveness against emerging pollutants (Komal et al., 2025).

In addition, membrane technology offers distinct advantages compared to other new water treatment technologies in providing a broader perspective on its role in addressing water purification challenges (Ji et al., 2023). Electrocoagulation requires high energy and produces sludge, whereas membrane technology enables efficient contaminant removal without chemicals. Although membranes provide modularity and scalability, fouling remains a challenge. Bio-inspired filtration shows selectivity but faces scaling problems. With advances in composite materials, membrane technology offers proven solutions. Its evolution through nanomaterials makes it crucial for sustainable water treatment (L. Zhang et al., 2024).

In this context, membrane technology has emerged as a promising solution because it offers higher energy efficiency, environmentally friendly processes, and operational ease without the need for additional chemicals. Its working principle, which is based on physical separation, allows contaminants to be blocked based on size, charge, or chemical affinity, while clean water molecules can selectively pass through the membrane pores (Idriss et al., 2025).

The application of membrane technology has been receiving increasing attention as an effort to address the clean water crisis and environmental pollution for nearly a century (Figure 1) (Ding et al., 2025). However, the reliability of this system is greatly influenced by the physicochemical properties of the membrane material (Tang et al., 2024), such as pore size, surface roughness, chemical stability, and water contact angle. In particular, the hydrophilic or hydrophobic characteristics of the membrane surface affect permeability, selectivity, and resistance to fouling. Therefore, a deep understanding of the relationship between membrane structure and properties is crucial in developing efficient and sustainable water filtration systems (Lakhotia et al., 2018).

The design and optimization of membranes require a deep understanding of the relationship between their structure and functional properties. This is where the crucial role of materials physics becomes relevant, offering insights into how nanostructures and interfacial interactions influence membrane behavior under real-world conditions. This

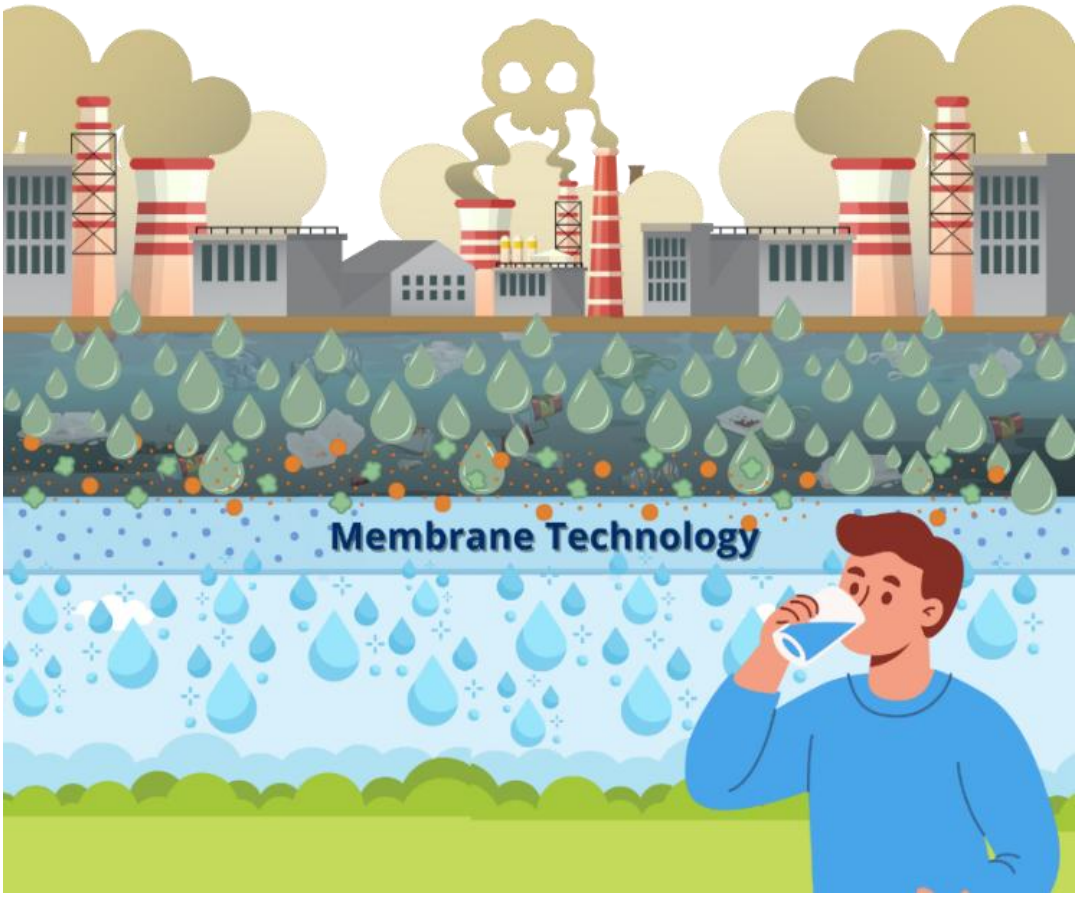

Figure 1. Transforming Polluted Water through Membrane Technology

review article presents a comprehensive analysis of recent developments in membrane materials, with a particular focus on the relationship between structural properties, including pore size distribution, water contact angle, and hydrophilic/hydrophobic characteristics. By presenting the latest findings from the scientific literature, we aim to open new avenues for the development of more efficient, sustainable, and adaptable water purification technologies in response to today's global water crisis challenges.

METHOD

The methodology employed in this study involved a structured literature search utilizing Harzing's Publish or Perish software. This tool facilitates the collection of bibliographic data from various databases, including Google Scholar. The search was guided by three specific keywords: "membrane material," "structure–property relationship," and "water treatment." To maintain the study's focus and ensure it remains representative, systematic, and unbiased towards any particular subtopic, the maximum number of results was limited to 100 articles.

The subsequent selection process was conducted manually, focusing on articles pertinent to the topic of membrane structure–property relationships in water treatment. The criteria for selection included articles written in English that contained quantitative data concerning the relationship between structural properties (such as pore size, hydrophilicity/ hydrophobicity, and contact angle) and membrane performance in water treatment. Articles that were not related to water studies, conference proceedings, or those lacking experimental data were excluded from consideration.

Subsequently, six representative studies were selected for comprehensive analysis, encompassing the types of materials, fabrication methods, surface characteristics, and filtration performance against various pollutants. This methodology ensures that the review's findings are systematic and elucidate a

clear relationship between the structure, properties, and performance of the membranes.

Fundamentals of Membrane Technology

Membrane filtration is a physical separation process that uses a semipermeable membrane to remove contaminants from a solution. This separation is carried out based on differences in particle size, pressure, and chemical properties between the molecules that pass through the membrane (permeate) and those that are retained (retentate). In membrane-based separation systems, the classification of membrane types based on pore size, operating pressure, and the types of contaminants that can be removed becomes an important element in determining the efficiency and applicability of the technology. Four main categories of membranes widely used in water treatment include Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis (RO), further explained in Table 1 .

Microfiltration has pore sizes ranging from 0.1 to 5 μm and operates at low pressure (0.1–2 bar), making it ideal for filtering solid suspensions and bacteria in applications such as drinking water pretreatment and the food industry. However, its limitation lies in its inability to filter out small molecules and dissolved substances (Danyo et al., 2023).

From the physicochemical perspective, large pore size provides high permeate flux but low selectivity, while a less hydrophilic surface increases the risk of fouling due to the attachment of organic particles. Therefore, surface modification to enhance hydrophilicity is often applied to extend the operational lifespan of MF membranes (Chen et al., 2022).Ultrafiltration features smaller pore sizes (0.01–0.1 μm) and operates at higher pressures (1–10 bar), capable of removing macromolecular-sized contaminants such as viruses, proteins, and complex organic compounds. This technology is widely applied in wastewater processing and the purification of bioproducts like enzymes (Melanie et al., 2022). UF performance is influenced by the balance between pore size and hydrophilicity; more hydrophilic membranes exhibit higher permeability and better fouling resistance. In addition, surface charge plays an important role in repelling charged contaminants through electrostatic force mechanisms, especially in water conditions with high ion content (Dobosz et al., 2017). Furthermore, Nanofiltration occupies a position between UF and RO, with pore sizes around 0.001–0.01 μm (1–10 nm) and an operating pressure of 4–30 bar. NF membranes are able to filter divalent ions (such as Ca^{2+}, Mg^{2+}) and small organic compounds, making them suitable for partial desalination and the removal of heavy metals from industrial wastewater (Samanta et al., 2023).

Table 1. Classification of Membrane Types Based on Structure and Function

Types of Membranes	Pore Size	Operating Pressure	Types of pollutants	Common Applications	Ref
Microfiltration (MF)	0.1–5 μm	0.1 – 2 bar	Solid suspensions, bacteria	Drinking water pretreatment, food industry	(Cheng et al., 2018; Hernández et al., 2022; Jassim et al., 2024; Warsinger et al., 2018; Yang et al., 2019; Zulkefli et al., 2021)
Ultrafiltration (UF)	0.01–0.1 μm	1 – 10 bar	Viruses, proteins, organic macromolecules	Wastewater treatment, enzyme purification	
Nanofiltration (NF)	0.001–0.01 μm (1 – 10 nm)	4 – 30 bar	Divalent ions, small organic compounds	Partial desalination, heavy metal removal	
Reverse Osmosis (RO)	< 0.001 μm (<1 nm)	30 – 70 bar	Monovalent ions, dissolved salts, small molecules	Seawater desalination, industrial ultrapure water	

Its efficiency greatly depends on the interaction between pore size and surface charge; membranes with a negative charge are more effective at rejecting positively charged ions (such as Ca^{2+}), while high hydrophilicity helps reduce fouling caused by dissolved organic compounds. The combination of these properties makes NanoFilter superior in maintaining a balance between ion selectivity and energy consumption (Sarkar et al., 2021).

Reverse Osmosis, as the most selective separation technology, has a pore size of <0.001 μm and requires high pressure (30–70 bar). RO is effective in removing monovalent ions, dissolved salts, and small organic molecules, making it highly suitable for seawater desalination applications and the production of ultrapure water in the semiconductor and pharmaceutical industries.

In the context of physicochemistry, very small pore sizes provide maximum selectivity but cause high flow resistance. Therefore, surface engineering by increasing hydrophilicity and controlling surface charge becomes key to minimizing fouling and maintaining stable flux at high pressure (Liu et al., 2019).

In general, this indicates that the smaller the pore size of a membrane, the higher its selectivity toward contaminants. Additionally, the relationship between surface charge and hydrophilicity becomes a key factor in achieving a balance between permeability, selectivity, and resistance to fouling. Increasing hydrophilicity and controlling surface charge have been proven to enhance membrane performance across various filtration scales, from MF to RO. However, this is accompanied by the need for higher operating pressures. A deep understanding of the interactions among these properties serves as an essential foundation for the structure–property–performance relationship approach in developing a new generation of efficient and sustainable membranes for water treatment. Therefore, the selection of membrane type must consider not only separation efficiency but also technical and economic aspects, based on the ultimate goal of the water treatment process.

Important Parameters in Membrane Filtration

In the membrane filtration process, a number of physicochemical parameters play a crucial role in determining the efficiency and effectiveness of separation. These parameters influence not only the fluid flow through the membrane but also contribute to selectivity, resistance to fouling, and long-term stability. Some of the most important among them include pore size, contact angle, operating pressure, as well as surface properties such as hydrophilicity or hydrophobicity. A thorough understanding of these parameters is essential in the design and optimization of membrane-based separation systems, especially in water and wastewater treatment applications (Tanne et al., 2019; L. Q. Zhang et al., 2013).

Pore Size

Pore size is a crucial parameter that directly determines the selectivity of the membrane in the separation process. In low-pressure filtration systems such as microfiltration and ultrafiltration, pore size determines the size threshold of particles or molecules that can be retained by the membrane. The smaller the pore size, the greater the membrane's ability to retain contaminants such as bacteria, viruses, microplastics, and large organic molecules. Conversely, pores that are too large can lead to low rejection efficiency, allowing contaminants to pass through into the permeate (Mora et al., 2019; Siddiqui et al., 2016).

In addition to playing a role in selectivity, pore size also affects the rate of water flux and the potential for fouling. Membranes with larger pore sizes generally have higher flux due to lower flow resistance, but they are also more susceptible to contamination and a decline in separation quality. Therefore, pore size design must take into account the trade-off between separation efficiency and operational stability Figure 2. Optimizing pore size is often combined with surface modification to

enhance overall performance, particularly in complex water purification applications (Jang et al., 2017; Yue et al., 2021).

Operating Pressure

Operating pressure plays a crucial role in determining the separation efficiency in membrane processes, as it directly affects the fluid flow rate (flux) and the membrane's ability to retain and separate contaminants. The higher the applied operating pressure, the greater the driving force that pushes water and small molecules through the membrane pores, thereby increasing filtration flux. However, separation efficiency also heavily depends on the mechanical limitations and pore structure of the membrane itself—excessively high pressure can cause membrane deformation, pore enlargement, or even structural damage that reduces selectivity (Santos et al., 1991).

Additionally, operating pressure also impacts membrane fouling. At excessively high pressures, suspended particles or dissolved substances tend to be forced more strongly against the membrane surface, accelerating the formation of fouling layers and increasing the total resistance. This, in turn, reduces long-term efficiency, as permeation rate decreases and required energy increases. Therefore, adjustments to operating pressure must take into account the membrane's design limits, the type of contaminants, and other system parameters to optimize separation efficiency while extending membrane service life (Omar et al., 2020).

Contact Angle

The contact angle is an important parameter representing the wettability of a membrane surface and directly affects separation efficiency. Membranes with a low contact angle (<90°) are hydrophilic, meaning they have a high affinity for water, which allows water to penetrate the membrane surface more easily and increases flux. This hydrophilic property also helps reduce interactions between contaminants (such as oil or organic substances) and the membrane surface, leading to lower fouling potential and enabling long-term maintenance of separation selectivity (bin Mohd Amiruddin et al., 2022; Chan et al., 2018).

On the other hand, membranes with a high contact angle (>90°) are hydrophobic; they tend to repel water, resulting in slower water penetration and lower flux, but can be more selective toward non-polar molecules. In certain specific applications, such as oil-water separation or membrane distillation, hydrophobic characteristics are actually required to prevent water penetration and

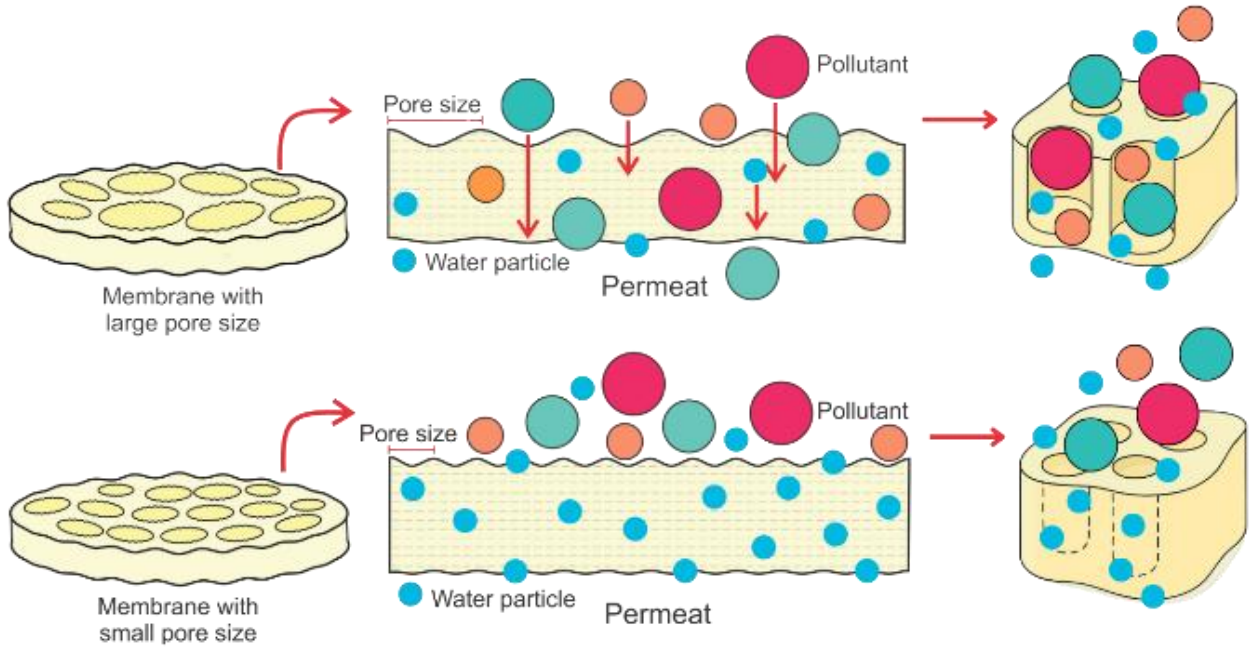

Figure 2. Role of pore size in separation efficiency

facilitate vapor transfer. Thus, the careful selection and engineering of the contact angle are crucial to the success of separation applications, depending on the targeted fluid type and the transport mechanisms involved (Wei et al., 2018).

Hydrophobicity and Hydrophilicity

The surface properties of membranes determine the interaction between water and the membrane. Hydrophilic membranes tend to have lower fouling resistance because they attract water and resist interactions with hydrophobic compounds. Conversely, hydrophobic membranes may more easily accumulate organic contaminants. Based on their affinity for water, membranes can be classified into two main categories: hydrophobic and hydrophilic. Hydrophilic membranes exhibit high affinity for water, characterized by a water contact angle < 90°, which indicates strong interaction between the membrane surface and water molecules. On the other hand, hydrophobic membranes repel water, have a contact angle > 90°, and interact only weakly with water, so their surfaces are not easily wetted (Wu et al., 2019). The differences between hydrophilic and hydrophobic membranes is shown in Table 2.

The surface properties of membranes, particularly their level of hydrophilicity or hydrophobicity, are crucial parameters that greatly affect filtration performance, including permeability, resistance to fouling, and compatibility with the intended application environment (Figure 3). Hydrophilic membranes have a high affinity for water (contact angle < 90°), allowing water to easily pass through the membrane pores and providing high permeability. This property makes them ideal for applications such as drinking water filtration, protein separation, and hemodialysis membranes. Conversely, hydrophobic membranes have a contact angle > 90°, repel interaction with water, and tend to retain water on their surface, making them more suitable for oily wastewater treatment, gas ventilation, and vapor separation (Casado-Coterillo et al., 2020).

Table 2. Differences between Hydrophilic and Hydrophobic Membranes

Characteristics	Hydrophilic Membranes	Hydrophobic Membranes	Ref
Definition	Membranes characterized by a high affinity for water are easily wetted.	Membranes that repel water; their surfaces are not easily wetted.	(Himma et al., 2019; G.-S. Kang et al., 2020; J. Kang et al., 2025; Kujawa et al., 2014; Xiong et al., 2020; Zhao et al., 2019)
Water Contact Angle	< 90° (signifies a strong interaction between water and the surface).	> 90° (indicating a weak interaction between water and the surface).	
Water Permeability	High permeability allows water to pass readily through the pores.	low permeability results in water being retained on the surface.	
Antifouling Properties	The material effectively reduces the adhesion of organic contaminants.	it is prone to fouling, as it is easily adhered to by oily substances or biofilms.	
Surface Properties	Polar, often containing hydroxyl (-OH) and carbonyl groups	Non-polar, often contain methyl groups (-CH_3)	
Material Examples	Polyethersulfone (PES), Polyvinyl Alcohol (PVA), Cellulose Acetate	Polytetrafluoroethylene (PTFE), Polypropylene (PP), PVDF (unmodified)	
Common Applications	Drinking water filtration, protein separation, and hemodialysis membranes	Oily wastewater treatment, gas venting, and vapor separation	
Water Stability	Exhibits stability and suitability for applications involving water.	Demonstrates reduced stability in moist environments, often necessitating modification.	

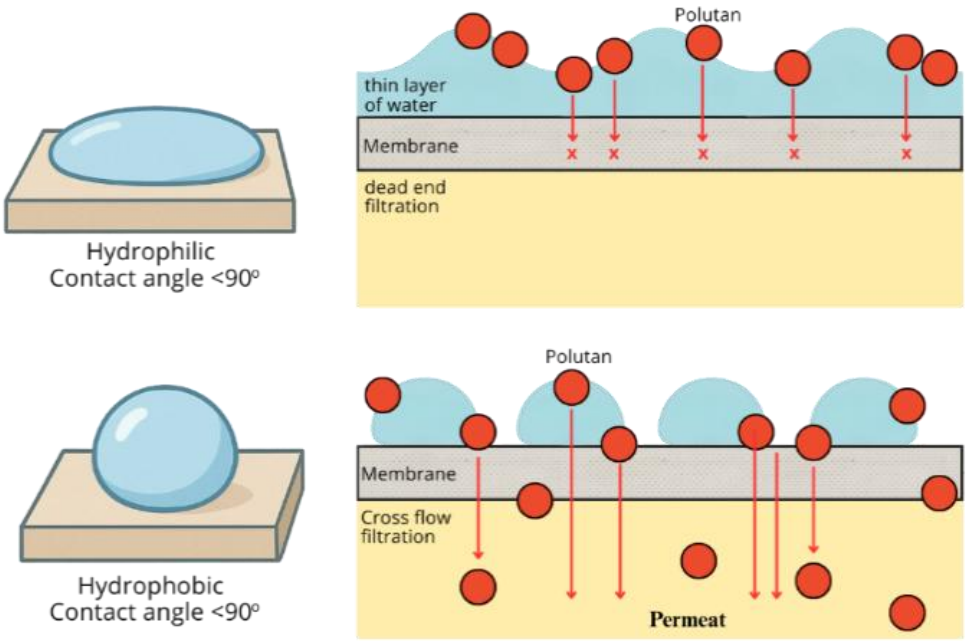

Figure 3. Schematic Comparison of Hydrophilic and Hydrophobic Membranes in Dead-End and Cross-Flow Filtration Modes

From the fouling perspective, hydrophilic membranes, which are polar and contain hydroxyl or carbonyl groups, are generally more resistant to the adhesion of organic contaminants or biofilms. On the other hand, hydrophobic membranes, which are non-polar, are prone to fouling from oily substances and thus often require additional modification. Examples of hydrophilic materials include PES, PVA, and Cellulose Acetate, while hydrophobic membranes are typically made from unmodified PTFE, PP, or PVDF as the base material. Additionally, hydrophilic membranes are generally more stable under wet conditions, whereas hydrophobic membranes often require enhanced stability through structural modification. Therefore, the selection of membranes based on their surface properties must take into account the fluid characteristics and intended separation application (Casado-Coterillo et al., 2020).

In practical applications, parameters such as pore size, operating pressure, contact angle, as well as the degree of hydrophilicity and hydrophobicity do not work independently; instead, they interact synergistically to determine membrane filtration performance (Meng et al., 2019). The optimal pore size must be matched to the membrane surface properties to balance permeability and selectivity while minimizing fouling (Jeon et al., 2016).

For example, hydrophilic membranes with small pore sizes generally exhibit better fouling resistance in wastewater treatment due to weaker interactions between the membrane surface and organic compounds (AlSawaftah et al., 2022). Conversely, hydrophobic membranes operated at high pressure may deliver high initial flux but are more susceptible to performance decline due to the buildup of non-polar contaminants (El Batouti et al., 2021; Feng et al., 2021). Therefore, an integrated understanding of the interrelations among these parameters is key to the design and optimization of membrane-based separation systems and supports a structure–property–performance relationship approach in the development of modern membrane materials for water treatment.

Permeability and Selectivity

Two key performance parameters in membrane systems are permeability (the ability of water or solvent to pass through the membrane) and selectivity (the membrane's ability to retain certain substances). In membrane development, there is a trade-off between the two: increasing permeability often lowers selectivity, and vice versa. Therefore,

membrane material design must carefully balance both, depending on the intended application (Iida et al., 2016).

Resistance to Fouling

Fouling is one of the main challenges in membrane filtration applications, referring to the accumulation of substances such as suspended particles, organic compounds, microorganisms, and biofilms on the membrane's surface or within its pores. This accumulation significantly reduces membrane performance, indicated by a decrease in flux, an increase in operating pressure, and a decline in separation efficiency. Fouling resistance is strongly influenced by various membrane surface properties, including surface energy, surface charge, roughness, and hydrophilic or hydrophobic characteristics (Hui et al., 2015).

Membranes with hydrophilic surfaces generally show better fouling resistance because they tend to repel contaminants with similar charges. To enhance antifouling properties, various strategies have been developed, such as chemical surface modification with hydrophilic groups (for example, –OH or –COOH), the use of protective layers like polymer brushes or self-assembled monolayers, and the incorporation of functional materials such as graphene oxide, titanium dioxide (TiO_2), or zwitterionic compounds. These materials enhance resistance to foulants through steric, electrostatic, or photocatalytic effects, thus extending membrane lifespan and reducing the cleaning frequency required in water and wastewater separation systems (Jaleh et al., 2020; Ngo et al., 2020; Tang et al., 2022).

Relationship Between Surface Morphology and Membrane Performance

Surface morphology is a crucial factor in determining the efficiency and stability of membrane performance during filtration processes. Parameters such as surface roughness, pore structure, pore size distribution, and pore orientation directly affect flux rate, selectivity, and fouling resistance. Surfaces that are too rough tend to facilitate contaminant buildup, especially by microorganisms and colloidal particles, increasing the risk of biofouling and pore blockage. Conversely, smooth, uniform, and evenly distributed pore structures can reduce flow turbulence and promote more precise separation (Karaiskakis et al., 2017) . Advanced fabrication technologies like electrospinning, phase inversion, and self-assembly are employed to engineer membrane morphology according to the needs of specific applications. For example, electrospinning enables the formation of nanofibrous membranes with high surface area and controlled porosity, while phase inversion can produce asymmetric membranes with a thin selective layer and a porous support layer. By precisely controlling morphology, filtration performance can be significantly improved, both in terms of separation efficiency and resistance to performance degradation caused by fouling or high operating pressures (Moinuddin et al., 2020) .

Membrane Materials: A Materials Physics Approach

The selection of membrane material is a crucial aspect in the design and optimization of filtration systems, as it directly affects mechanical strength, thermal stability, porosity, and fouling performance. Membrane materials are generally classified into four main groups: polymeric, ceramic, metallic, and composite (both polymer-ceramic and nanocomposite). Each type has distinctive physical characteristics, as summarized in Table 3.

Polymeric materials such as Polyethersulfone (PES), Polyvinylidene Fluoride (PVDF), and Cellulose Acetate (CA) are widely used due to their high flexibility, low cost, and ease of fabrication. However, the main drawbacks of polymeric membranes are their low mechanical strength and thermal stability, as well as their susceptibility to fouling (Wang et al., 2023) . Although cost-efficient and easy to manufacture, pure polymer membranes generally have a limited lifespan and require regular cleaning due to fouling. In long-term applications, their performance tends to decline more quickly

compared to inorganic or composite membranes. However, because their production is highly scalable, this material remains the primary choice for large-volume applications such as drinking water ultrafiltration (Baghbanzadeh et al., 2016).

Ceramic membranes such as alumina (Al_2O_3), silica (SiO_2), and titanium dioxide (TiO_2) offer very high mechanical strength and thermal stability, making them ideal for filtering corrosive fluids or at high temperatures, although they tend to be expensive and difficult to form into thin structures (Mataram et al., 2021). In terms of long-term performance, ceramic membranes demonstrate excellent stability and fouling resistance, even under extreme conditions. However, the high cost of materials and fabrication processes remains a major obstacle to large-scale implementation. Therefore, their use is more focused on high-value industrial applications or environments with extreme operating conditions (Abdullayev et al., 2019; Jarrar et al., 2024).

Metals, such as stainless steel and titanium, excel in resistance to extreme pressure and temperature but are heavy, costly, and prone to corrosion without special coatings (Senthil Muthu Kumar et al., 2021). Metal membranes offer exceptional advantages in mechanical strength and resistance to high pressure, but production costs and the risk of long-term corrosion reduce economic efficiency in water applications. In industrial practice, metal membranes are more commonly used in specialized systems such as the filtration of corrosive fluids or high-temperature gas separation processes, rather than for large-scale water treatment (Zhu et al., 2018).

Meanwhile, composite membranes combine the advantages of two or more materials, for example PVDF-graphene oxide, PES-TiO_2, or PAN-CNT, resulting in multifunctional structures with improved fouling resistance, catalytic activity, or enhanced selectivity. The thermal stability of composites is generally in the intermediate range (200–300 °C) with mechanical strength that can be tailored. The pore size in composite materials is also flexible, ranging from 0.01–1 μm, allowing for targeted designs according to the application (Issa et al., 2016). Composite membranes are able to overcome the limitations of pure polymers by combining the mechanical strength and thermal stability of inorganic materials. In the long term, composite membranes demonstrate better fouling resistance and a longer service life, although their synthesis costs are still relatively high. However, with advances in fabrication technologies such as phase inversion-assisted coating and electrospinning, the production of composite membranes is becoming increasingly scalable for modern water industry applications (Du et al., 2020).

Overall, there is no single type of material that is superior in all aspects. Polymeric membranes excel in terms of cost and ease of production, while ceramic and metal membranes stand out for their durability and stability. However, their main challenges are high costs and limited scalability. The composite approach offers a new balance by combining the mechanical and thermal advantages of inorganic materials with the flexibility of polymers, making it the most promising direction for long-term development in clean water treatment applications. Physical characteristics such as mechanical strength determine the membrane's resistance to operational pressure, while porosity and pore size affect filtration flux and particle separation efficiency. On the other hand, thermal stability becomes crucial in high-temperature applications, such as thermal desalination or aggressive chemical processing. Materials such as TiO_2 or CNTs also demonstrate beneficial antifouling and photocatalytic properties in light-based water purification systems or complex organic-contaminated environments. Thus, membrane material selection cannot be uniform, but must be tailored to specific operational parameters, fluid properties, and end-use objectives (Sun et al., 2019). The combination of the physical and chemical properties of the material with the appropriate surface morphology design will determine the long-term effectiveness of the membrane in modern water filtration applications.

Table 3. Membrane Materials and Their Physical Characteristics

Membrane Materials	advantages	disadvantages	Mechanical Strength	Thermal Stability	Pore Size	Materials used	Common Applications	Ref
Polymeric	Low cost, easy to fabricate, flexible	Susceptible to fouling and chemical/thermal degradation	Low–medium; flexible, easily deformed	Low–moderate (< 100°C)	High (~50%); pores 0.01–5μm	Polyethersulfone (PES), Polyvinylidene Fluoride (PVDF), Cellulose Acetate (CA), Polyacrylonitrile (PAN)	Ultrafiltration of drinking water, hemodialysis, wastewater treatment	(Adegoke et al., 2023; Arumugham et al., 2021; Divya et al., 2022; Hofs et al., 2011; Juarez et al., 2021; Kujawa et al., 2017)
Ceramic	Chemically and thermally stable, fouling resistant	Expensive, rigid, and difficult to process in thin layers	High; stiff, corrosion and abrasion resistant	Very high (> 500°C), stable against acids/bases	Medium (~30–40%); pores 0.01–1μm	Alumina (Al_2O_3), Silika (SiO_2), Zirconia (ZrO_2), Titanium dioxide (TiO_2)	Industrial wastewater, hot/corrosive water, desalination	
Metal	Strong, high pressure resistant, extreme temperature resistant	Heavy, expensive, and prone to corrosion without coating	Very high; withstands heavy pressure and loads	Very high (> 700°C), depending on the metal type	Depends on the process (usually <1μm)	Stainless steel, Titanium, Nikel	Gas separation, filtration of corrosive fluids in heavy industry	
Composite	Multifunctional, customizable, fouling resistant	Complex synthesis process; long-term stability is not optimal	Customized; better than pure polymers	Medium–high (~200–300°C)	Pore size can be adjusted (0.01–1μm)	PES-TiO_2, PVDF-Graphene oxide, CA-ZnO, PAN-CNT	Multifunctional membranes: antifouling, catalytic, selective separation	

DISCUSSION OF MEMBRANE PERFORMANCE IN WATER POLLUTION MANAGEMENT

Evaluation of membrane performance in water pollution management is essential to assess the effectiveness of this technology in various applications. Membrane performance is greatly influenced by the structural properties of its constituent materials, such as the degree of hydrophilicity or hydrophobicity, pore size, and water contact angle, which directly determine its efficiency. These three parameters interact and collectively define the structure–function relationship in membrane-based separation technology. Table 4 summarizes data from various recent studies regarding membrane material types, hydrophilic/hydrophobic properties, synthesis methods, pore sizes, contact angles, as well as separation performance for pollutants such as heavy metals, microplastics, oil, and dyes. Accordingly, this section not only highlights operational performance but also emphasizes critical comparisons between materials, emerging limitations, and the direction of membrane design development for practical applications in domestic and industrial wastewater treatment.

One of the most consistent findings across all journals is that membranes with hydrophilic properties demonstrate better separation performance compared to hydrophobic membranes. Hydrophilic surfaces allow water to more easily wet and pass through the membrane pores, as well as form a thin layer of water that functions to inhibit fouling by oil, proteins, and other organic contaminants. This can be seen in the study by Nayak et al. (2025), where cellulose acetate (CA) membranes modified with a combination of amino acids and ionic liquids exhibited a contact angle of 63°, a flux of 10–12 L/m²·h·bar, and heavy metal (Cu, Zn, Fe, Pb) rejection efficiency of up to 94% (Nayak et al., 2025). The reported flux value was measured at an operating pressure of 4 bar, with a variation of ±5% due to the pH conditions of the wastewater.

Similar findings were also reinforced by Kiamehr et al. (2025), who coated PES membranes with a diamond-like carbon (DLC) layer, thereby reducing the contact angle to 42°, smoothing the surface roughness (from 16 nm to 9 nm), and increasing the water flux from 8 to 65 L/m²·h·bar. In addition, salt rejection efficiency increased from 64% to 98% (Kiamehr et al., n.d.). Conversely, membranes with hydrophobic properties such as PVDF–MOF in the study by Rojjanapinun (2021) showed a high contact angle (119.5°) with low flux (2.45 L/m²·h·bar), although they still achieved high rejection efficiency for SMX, BSA, and even the SARS-CoV-2 virus. This indicates that although separation capability can be maintained, hydrophobic properties inhibit water flow and increase the potential for fouling (Rojjanapinun et al., 2021). Based on this comparison, it can be concluded that increasing hydrophilicity not only enhances flux but also extends the operational lifespan of the membrane by reducing irreversible fouling. However, increasing hydrophilicity through surface modifications such as the addition of DLC or biosurfactants often requires additional processes and higher costs compared to bulk modification, which becomes the main trade-off between performance efficiency and production complexity.

The water contact angle is an important parameter that quantitatively indicates the degree of hydrophilicity of a membrane surface. A value below 90° indicates a hydrophilic surface that interacts more favorably with water. For example, the lowest contact angle was recorded on the DLC membrane by Kiamehr et al. (2025) at 42°, which contributed to high flux and better fouling resistance. Although some studies, such as those by Yu et al. (2025), Nayak et al. (2025), and De Rosset et al. (2024), did not directly report the contact angle value, the increase in hydrophilicity through surface modification with hydrogels, biosurfactants, or ionic liquids implicitly reduced the contact

angle and supported improved filtration performance (Kiamehr et al., n.d.; Nayak et al., 2025; Yu et al., 2025).

Comparatively, modifications based on natural materials such as chitosan or rhamnolipid tend to increase hydrophilicity without compromising environmental sustainability, whereas inorganic approaches such as DLC or Fe–SiO_2 are superior in terms of thermal stability and mechanical resistance, but are less environmentally friendly and may potentially increase production costs. In addition to contact angle parameters, the hydrophilic or hydrophobic properties of a membrane can also be evaluated through a work of adhesion (WoA) test, which measures the energy required to separate two phases—usually water and the membrane surface (Zhang et al., 2015). The WoA value can be calculated using the Dupré–Young equation:

$$W_A = \gamma_L(1 + \cos\theta) \quad (1)$$

where WA is the adhesion energy (mJ/m²), is the surface tension of the liquid (water = 72.8 mJ/m² at 20 °C), and θ is the water contact angle. According to this equation, the smaller the water contact angle, the greater the value of WoA, which means the interaction between water and the membrane surface is stronger (Xiu et al., 2008). For example, a membrane with a contact angle of 42° (Kiamehr et al., n.d.), shows a WoA of around 125 mJ/m², while the hydrophobic membrane with a contact angle of 119.5°(Rojjanapinun et al., 2021), has a WoA of only about 30 mJ/m². This is consistent with experimental results showing that hydrophilic surfaces facilitate water wetting and strengthen the liquid–solid interface, thereby increasing permeability and reducing fouling (Clint et al., 2001).

WoA testing also provides a quantitative basis for assessing the effectiveness of surface modifications. Several studies indicate that an increase in WoA above 100 mJ/m² generally correlates with improved water flux and long-term fouling resistance (Palencia, 2017)Thus, the integration of contact angle analysis and work of adhesion provides a more comprehensive understanding of the relationship between surface structure, interfacial interaction energy, and filtration performance.

Besides surface properties, pore size is an important factor that determines the selectivity of a membrane. Membranes with larger pore sizes tend to have higher flux but lower selectivity for small molecules. For example, PVDF produced by the electrospinning method in the study by Yu et al. (2025) has a pore size of around 392 nm and is able to produce very high flux, while still being effective in separating large molecules such as dyes (Yu et al., 2025). On the other hand, Yuliati (2012) reported PSf membranes with a pore size of 0.0014 μm (1.4 nm) suitable for treating turbid river water, with a color reduction efficiency of up to 87.94%, although with a relatively low flux (Yuliati Selastia, 2012).

The correlation between pore size and performance was also demonstrated by Rojjanapinun (2021), who produced an isoporous structure measuring 20–100 nm using PVDF–RHA and MOF (Rojjanapinun et al., 2021), resulting in high rejection of pharmaceutical compounds and viruses. Azizi et al. (2023) demonstrated that modification of PES with M–Fe_3O_4 nanoparticles produces a stable pore structure with a flux of 21 L/m²·h·bar and a combined rejection efficiency for heavy metals and dyes of up to 98% (Azizi et al., 2023). The success of De Rosset et al. (2024) in filtering microplastics as small as 0.5 μm also underscores the importance of pore structure regulation and surface properties; modification with biosurfactants as well as TiO_2 and CuO nanoparticles on PVDF increases flux up to 3100–6000 L/m²·h·bar and oil as well as microplastic rejection efficiency to more than 90% (De Rosset et al., n.d.). The flux range was measured at a pressure of 1 bar for the oil-water emulsion, with a deviation of ±8% due to differences in microplastic particle size in the test solution.

From the comparative data, a clear trade-off between flux and selectivity can be observed: the larger the pore size, the higher the

resulting flux, but selectivity for small molecules decreases. Conversely, small pore sizes provide high rejection rates for heavy metals and viruses, but come with a higher risk of fouling and require greater operating pressure. Therefore, precise control of pore size—through techniques such as phase inversion with pore-regulating additives or layered electrospinning—becomes an important strategy to achieve a balance between permeability and selectivity, depending on the type of pollutant being targeted.

When compared comprehensively, the base materials of membranes exhibit their own unique characteristics and limitations. PVDF-based membranes possess high chemical and thermal stability, but their inherently hydrophobic nature often requires additional modifications such as MOFs or biosurfactants to enhance performance. PES offers a balance between mechanical strength and the flexibility of surface modification, but it is prone to fouling when used in water with high organic content. Meanwhile, cellulose acetate (CA) demonstrates natural hydrophilic and environmentally friendly properties, but its drawbacks lie in low thermal stability and degradation under extreme pH conditions (Nayak et al., 2025).

Surface modifications such as DLC coatings (Kiamehr et al., n.d.), or the use of natural biosurfactants (De Rosset et al., n.d.), demonstrate two different approaches: the former highlights enhanced mechanical properties and long-term durability, while the latter emphasizes sustainability and low cost. The hybrid approach, such as the combination of metal oxide nanoparticles and organic compounds, offers a middle ground by enhancing hydrophilicity and separation capacity without compromising structural stability. However, there are still common limitations across all types of modifications, such as non-uniform nanoparticle distribution, decreased flux after repeated filtration cycles, and potential issues of modified material release into the environment. These aspects indicate that future membrane development needs to focus on long-term stability and environmental safety, not just initial efficiency improvements.

Overall, it can be concluded that a high level of hydrophilicity (low contact angle) consistently increases water flux, reduces fouling potential, and is effective for the separation of organic pollutants and oil. Large pore sizes (hundreds of nanometers) provide high flux and are suitable for the separation of large molecules such as dyes or microplastics, but require additional modifications to enhance selectivity. On the other hand, small pore sizes (submicron) are suitable for filtering heavy metals and viruses, but are prone to fouling and require optimal control of operating pressure. Additional modifications such as the addition of nanoparticles, surfactants, and functional compounds (MOF, DLC, Fe–SiO_2) have been proven to increase hydrophilicity, optimize pore structure, and enhance separation efficiency and stability.

Synthesis from various studies shows that the structure–property–performance relationship is not linear, but rather complex and contextual to operating conditions and the type of pollutant. For example, increasing extreme hydrophilicity does not always result in the highest flux if the pore structure is not distributed homogeneously. Moving forward, a promising research direction is the development of data-driven design and predictive modeling based on artificial intelligence (AI/ML) to optimize the relationship between structural parameters and membrane performance. In addition, the use of natural materials and environmentally friendly processes needs to be continually expanded to support sustainability principles. By synergistically integrating the three structural parameters—hydrophilicity/ hydrophobicity, pore size, and contact angle—and considering the trade-offs between performance, stability, and sustainability, it is possible to develop membranes that are efficient, selective, and durable to address future water treatment challenges, both on an industrial scale and in natural environments.

Table 4. Evaluation of membrane structure properties on its performance

Ref	Fabrication process			membrane properties			key performance			Application	Water Source	Comparative Insights
	main material	additional material	applied method	types	porositas membrane (nm)	water contact angle	permeation study (L/m²·h·bar)	rejection (%)	pollutant			
(Rojjanapinun et al., 2021)	PVDF	RHA	solvethermal	hydrophilic	20	88.3	2,475	98	-	Turbid water and the SARS-CoV-2 virus	river water	MOF addition enhances virus and particle rejection while maintaining flux stability.
		MOF		hydrophobic	20	119,5	2,450	99				
(Yu et al., 2025)	PVDF	CNTs/COOH@TA-CS	electrospinning	hydrophilic	392.63	47	1,907.80	95	oil Methylene blue (MeB), Rhodamine B (RB), Congo Red (CR), Methyl Blue (MB)	Oil and dye waste filters	an oil-in water emulsion dye waste	CNTs improve porosity and selectivity, making it effective for oily waste.
(Nayak et al., 2025)	CA	AA/Ils	Phase Inversion	hydrophilic	0.0110	63	10, and 12	89 - 90	heavy metal: Copper, Zinc, iron, lead present in industrial effluent	Metal separators	metal industry waste in Tiruchirappalli, Tamil Nadu, India.	Ionic liquid additives improve hydrophilicity and heavy-metal rejection.
(Hofs et al., 2011)	PES	DLC	-	hydrophilic	6	42	59	98	salt	Salt separators	sodium sulfate salt solution	Good salt rejection, limited flux due to dense morphology.

Ref	Fabrication process			membrane properties			key performance			Application	Water Source	Comparative Insights
	main material	additional material	applied method	types	porositas membrane (nm)	water contact angle	permeation study (L/m²·h·bar)	rejection (%)	pollutant			
(De Rosset et al., n.d.)	PVDF	biosurfactant/metal oxides (TiO2)	electrospinning	hydrophilic	0.75	105 (TiO2)	6000 (microplastic), and 500 (oil)	100, and 95	microplastic and oil	removal microplastic and oil	-	TiO_2 improves microplastic rejection; CuO enhances oil removal.
		biosurfactant/metal oxides (CuO)		hydrophobic	0.75	78 (CuO)	3100 (microplastic), and 1850 (oil)	92, and 94				
(Azizi et al., 2023)	PES	M-Fe3O4	phase separation	hydrophilic	-	52	21 (copper), and 15 (DR16 dye)	68 - 84, and 98	copper, and DR16	removal heavy metals and dye	-	Magnetic particles facilitate recovery and strong adsorption of heavy metals.

in filtering large molecules such as dyes. Conversely, Yuliati (2012) used a PSf membrane with a pore size of 0.0014 μm (1.4 nm), suitable for treating turbid river water, and could reduce color content by up to 87.94%, albeit with relatively low flux (Yuliati Jurusan Teknik Kimia Politeknik negeri Sriwijaya et al., n.d.).

The ability to filter pollutants based on pore size is also supported by Rojjanapinun and Pagsuyoin (2021), who produced an isoporous structure of 20–100 nm using PVDF–RHA and MOF, enabling high rejection of Pharmaceutical compounds and viruses [3]. Meanwhile, Azizi et al. (2023) showed that modification of PES with M–Fe_3O_4 nanoparticles resulted in membranes with a stable pore structure, high flux (21 kg/m²·h), and combined rejection efficiency for heavy metals and dyes up to 98% (Azizi et al., 2023). Furthermore, the success of De Rosset et al. (2024) in filtering microplastics of 0.5 μm size highlights the importance of adjusting pore structure and surface. Modification with biosurfactants and TiO_2 and CuO nanoparticles led to PVDF membranes with exceptionally high flux (3100–6000 L/m²·h·bar) and microplastic and oil rejection efficiency of >90% (De Rosset et al., n.d.). From the overall discussion, it can be concluded that: High hydrophilicity (low contact angle) consistently increases water flux, lowers fouling potential, and is effective for organic pollutants and oil. Large pore sizes (hundreds of nm) allow for high flux and are suitable for separating large molecules like dyes or microplastics, but often require additional modifications to enhance selectivity. Small pore sizes (sub-micron) are suitable for filtering heavy metals and viruses, but are prone to fouling and require optimal pressure control. Additional modifications such as nanoparticles, surfactants, and functional compounds (MOF, DLC, Fe–SiO_2) can enhance hydrophilicity, optimize pores, and increase efficiency and separation stability.

By integrating these three structural parameters—hydrophilic/hydrophobic properties, pore size, and contact angle—synergistically, efficient, selective, and durable membranes can be developed to address challenges in wastewater treatment, whether for industrial, domestic, or natural environmental applications.

FUTURE DIRECTION

As the demand for more efficient and sustainable water purification technologies increases, the development of membranes based on material structure–property approaches still holds substantial potential for further exploration. According to recent literature findings, future research directions can be focused on the following strategic points:

- Development of Multifunctional Materials Based on Nanotechnology: Future research should focus on utilizing functional materials such as graphene oxide, MOFs, and nanocomposites to enhance hydrophilicity, resistance to fouling, and membrane selectivity toward specific pollutants.
- Precise Engineering of Surface Morphology and Pore Structure: Optimizing pore size and distribution through techniques such as electrospinning or phase inversion is key to balancing high flux and separation efficiency.
- Integration of Hybrid and Responsive Systems: The combination of membrane technology with other processes such as photocatalysis or adsorption, as well as the development of smart membranes responsive to pH, light, or temperature, will further enhance adaptability to complex water conditions.
- Environmentally Friendly and Sustainable Approaches: Emphasizing membrane synthesis using biomaterials, renewable waste, and green fabrication processes will be an important direction to support sustainability in water treatment technology.
- Application of Artificial Intelligence (AI) and Machine Learning (ML): The

integration of AI and ML can accelerate membrane design and optimization through predictive design and data-driven operation approaches. Algorithms such as Artificial Neural Networks predict the relationship between material structure and performance (permeability, selectivity, fouling), while deep learning enables real-time monitoring for early fouling detection. This approach shifts from trial and error methods toward more efficient, sustainable, and longer-lasting adaptive systems in water treatment.

By emphasizing multidisciplinary collaboration between materials science, applied physics, environmental engineering, and artificial intelligence, the future of membrane technology is projected to become increasingly adaptive, selective, and capable of meeting complex challenges in the ever-evolving global water crisis.

CONCLUSION

Membrane technology has proven to be a promising solution in addressing the challenges of water pollution and clean water crises. The performance of membranes is highly determined by their structural characteristics, particularly surface hydrophilicity, pore size, and water contact angle. Membranes with hydrophilic properties (contact angle < 90°) tend to have higher water flux, better fouling resistance, and more optimal pollutant separation efficiency compared to hydrophobic membranes. Pore size also plays a crucial role in determining the types of pollutants that can be effectively filtered, ranging from microplastics to heavy metals and viruses.

In addition, various studies have shown that surface modification of membranes with functional materials such as nanoparticles, surfactants, and MOFs significantly enhances separation performance and long-term stability. The integration of these three key parameters—pore structure, surface properties, and contact angle—synergistically opens up great opportunities in developing more efficient, selective, and durable water filtration systems. This approach supports the creation of membrane technology that is adaptive to various types of contaminants and the water treatment needs of today and the future.

REFERENCES

Abdullayev, A., Bekheet, M., Hanaor, D., & Gurlo, A. (2019). Materials and Applications for Low-Cost Ceramic Membranes. *Membranes*, *9*(9), 105. doi: 10.3390/membranes9090105

Adegoke, K. A., Giwa, S. O., Adegoke, O. R., & Maxakato, N. W. (2023). Bibliometric evaluation of nanoadsorbents for wastewater treatment and way forward in nanotechnology for clean water sustainability. *Scientific African*, *21*, e01753. doi: 10.1016/j.sciaf.2023.e01753

AlSawaftah, N., Abuwatfa, W., Darwish, N., & Husseini, G. A. (2022). A Review on Membrane Biofouling: Prediction, Characterization, and Mitigation. *Membranes*, *12*(12), 1271. doi: 10.3390/membranes12121271

Arumugham, T., Kaleekkal, N. J., Gopal, S., Nambikkattu, J., K, R., Aboulella, A. M., Ranil Wickramasinghe, S., & Banat, F. (2021). Recent developments in porous ceramic membranes for wastewater treatment and desalination: A review. *Journal of Environmental Management*, *293*, 112925. doi: 10.1016/j.jenvman.2021.112925

Azizi, shahab, Jafarbeigi, E., & Salimi, F. (2023). Removal of heavy metals and dye from water and wastewater using nanofiltration membranes of polyethersulfone modified with functionalized iron-silica nanoparticles. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *45*(3), 6856–6868. doi: 10.1080/15567036.2023.2219222

Baghbanzadeh, M., Rana, D., Lan, C. Q., & Matsuura, T. (2016). Effects of Inorganic Nano-Additives on Properties and

Performance of Polymeric Membranes in Water Treatment. *Separation & Purification Reviews*, *45*(2), 141–167. doi: 10.1080/15422119.2015.1068806

bin Mohd Amiruddin, A. A. A., Chan, M. K., & Ng, S. (2022). *Development of Contact Angle Prediction for Cellulosic Membrane* (pp. 207–216). doi: 10.1007/978-3-030-93247-3_21

Casado-Coterillo, C., Garea, A., & Irabien, Á. (2020). Effect of Water and Organic Pollutant in CO2/CH4 Separation Using Hydrophilic and Hydrophobic Composite Membranes. *Membranes*, *10*(12), 405. doi: 10.3390/membranes10120405

Chan, M., & Ng, S. (2018). *Effect of membrane properties on contact angle*. 020035. doi: 10.1063/1.5055437

Chen, M., Heijman, S. G. J., Luiten-Olieman, M. W. J., & Rietveld, L. C. (2022). Oil-in-water emulsion separation: Fouling of alumina membranes with and without a silicon carbide deposition in constant flux filtration mode. *Water Research*, *216*, 118267. doi: 10.1016/j.watres.2022.118267

Cheng, X. Q., Wang, Z. X., Jiang, X., Li, T., Lau, C. H., Guo, Z., Ma, J., & Shao, L. (2018). Towards sustainable ultrafast molecular-separation membranes: From conventional polymers to emerging materials. *Progress in Materials Science*, *92*, 258–283. doi: 10.1016/j.pmatsci.2017.10.006

Dan, S., Membran, K., Dan, P., Asetat, S., Limbah, D., Rokok, F., Musyaffa, [, Zulfa Musyaffa, A., Fadillah, N., Maina Idriss, I., Nugroho, W. A., Bilad, M. R., & Wibisono, Y. (2024). Synthesis and Characterization of Polysulfone Membrane and Cellulose Acetate from Cigarette Butts Waste. In Jurnal Teknologi Pertanian (Vol. 25, Issue 2).

Danyo, E. K., Ivantsova, M., & Selezneva, I. (2023). Ionizing radiation effects on microorganisms and its applications in the food industry. *Foods and Raw Materials*, *12*(1), 1–12. doi: 10.21603/2308-4057-2024-1-583

De Rosset, A., Torres-Mendieta, R., Pasternak, G., & Yalcinkaya, F. (n.d.). *Synergistic Effects of Natural Biosurfactant and Metal Oxides Modification on PVDF Nanofiber Filters for Efficient Microplastic and Oil Removal*.

Ding, A., Wang, Y., Liu, Z., Li, S., Liang, H., & Bai, L. (2025). A low-carbon resource recycling pathway: cellulose nanocrystals (CNCs) membranes derived from waste paper pulp for efficient surface water treatment. *Journal of Membrane Science*, *734*. doi: 10.1016/j.memsci.2025.124451

Divya, S., & Oh, T. H. (2022). Polymer Nanocomposite Membrane for Wastewater Treatment: A Critical Review. *Polymers*, *14*(9), 1732. doi: 10.3390/polym14091732

Dobosz, K. M., Kuo-Leblanc, C. A., Martin, T. J., & Schiffman, J. D. (2017). Ultrafiltration Membranes Enhanced with Electrospun Nanofibers Exhibit Improved Flux and Fouling Resistance. *Industrial & Engineering Chemistry Research*, *56*(19), 5724–5733. doi: 10.1021/acs.iecr.7b00631

Du, Y., Huang, L., Wang, Y., Yang, K., Zhang, Z., Wang, Y., Kipper, M. J., Belfiore, L. A., & Tang, J. (2020). Preparation of graphene oxide/silica hybrid composite membranes and performance studies in water treatment. *Journal of Materials Science*, *55*(25), 11188–11202. doi: 10.1007/s10853-020-04774-5

El Batouti, M., Alharby, N. F., & Elewa, M. M. (2021). Review of New Approaches for Fouling Mitigation in Membrane Separation Processes in Water Treatment Applications. *Separations*, *9*(1), 1. doi: 10.3390/separations9010001

Feng, G., Huang, L., & Yang, Y. (2021). Characteristics of dissolved organic matter in surface water and fouling mechanisms during the ultrafiltration.

Desalination and Water Treatment, *238*, 53–66. doi: 10.5004/dwt.2021.27759

Hernández, K., Muro, C., Monroy, O., Diaz-Blancas, V., Alvarado, Y., & Diaz, M. del C. (2022). Membrane Water Treatment for Drinking Water Production from an Industrial Effluent Used in the Manufacturing of Food Additives. *Membranes*, *12*(8), 742. doi: 10.3390/membranes12080742

Himma, N. F., Prasetya, N., Anisah, S., & Wenten, I. G. (2019). Superhydrophobic membrane: progress in preparation and its separation properties. *Reviews in Chemical Engineering*, *35*(2), 211–238. doi: 10.1515/revce-2017-0030

Hofs, B., Ogier, J., Vries, D., Beerendonk, E. F., & Cornelissen, E. R. (2011). Comparison of ceramic and polymeric membrane permeability and fouling using surface water. *Separation and Purification Technology*, *79*(3), 365–374. doi: 10.1016/j.seppur.2011.03.025

Hui, L., Liu, M., Cai, Y., & Lv, Y. (2015). Fouling Resistance on Chemically Etched Hydrophobic Surfaces in Nucleate Pool Boiling. *Chemical Engineering & Technology*, *38*(3), 416–422. doi: 10.1002/ceat.201400194

Idriss, I. M., Hashmi, Z., Shamsuddin, N., Abu Bakar, M. S., Thongratkaew, S., Faungnawakij, K., Wibisono, Y., & Bilad, M. R. (2025). Dual-layer flat sheet membrane from waste cellulose acetate for natural organic matter removal from surface water. *Journal of Water Process Engineering*, *72*. doi: 10.1016/j.jwpe.2025.107625

Iida, R., Yonezu, T., Shinkawa, Y., & Nagai, K. (2016). Reversible selectivity of water/organic solvent mixtures in poly(lactic acid) film. *Journal of Applied Polymer Science*, *133*(33). doi: 10.1002/app.43822

Issa, A. A., Al-Maadeed, M. A. A. S., Mrlík, M., & Luyt, A. S. (2016). Electrospun PVDF graphene oxide composite fibre mats with tunable physical properties. *Journal of Polymer Research*, *23*(11), 232. doi: 10.1007/s10965-016-1126-y

Jaleh, B., Zare, E., Azizian, S., Qanati, O., Nasrollahzadeh, M., & Varma, R. S. (2020). Preparation and Characterization of Polyvinylpyrrolidone/Polysulfone Ultrafiltration Membrane Modified by Graphene Oxide and Titanium Dioxide for Enhancing Hydrophilicity and Antifouling Properties. *Journal of Inorganic and Organometallic Polymers and Materials*, *30*(6), 2213–2223. doi: 10.1007/s10904-019-01367-x

Jang, D., Idrobo, J.-C., Laoui, T., & Karnik, R. (2017). Water and Solute Transport Governed by Tunable Pore Size Distributions in Nanoporous Graphene Membranes. *ACS Nano*, *11*(10), 10042–10052. doi: 10.1021/acsnano.7b04299

Jarrar, R., Abbas, M. K. G., & Al-Ejji, M. (2024). Environmental remediation and the efficacy of ceramic membranes in wastewater treatment—a review. *Emergent Materials*, *7*(4), 1295–1327. doi: 10.1007/s42247-024-00687-0

Jassim, Z. S., Braihi, A. J., & Shabeeb, K. M. (2024). Polymeric Membranes for Industrial Wastewater Treatment: A Review. *International Journal of Environmental Impacts*, *7*(3), 395–408. doi: 10.18280/ijei.070302

Jeon, S., Rajabzadeh, S., Okamura, R., Ishigami, T., Hasegawa, S., Kato, N., & Matsuyama, H. (2016). The Effect of Membrane Material and Surface Pore Size on the Fouling Properties of Submerged Membranes. *Water*, *8*(12), 602. doi: 10.3390/w8120602

Ji, K., Liu, C., He, H., Mao, X., Wei, L., Wang, H., Zhang, M., Shen, Y., Sun, R., & Zhou, F. (2023). Research Progress of Water Treatment Technology Based on Nanofiber Membranes. *Polymers*, *15*(3), 741. doi: 10.3390/polym15030741

Juarez, E., Lasobras, J., Soler, J., Herguido, J., & Menéndez, M. (2021). Polymer–Ceramic Composite Membranes for Water Removal in Membrane Reactors.

Membranes, *11*(7), 472. doi: 10.3390/membranes11070472

Kang, G.-S., Baek, Y., & Yoo, J.-B. (2020). Relationship between surface hydrophobicity and flux for membrane separation. *RSC Advances*, *10*(66), 40043–40046. doi: 10.1039/D0RA07262A

Kang, J., Kwon, O., Kim, J. P., Kim, J. Y., Kim, J., Cho, Y., & Kim, D. W. (2025). Graphene Membrane for Water-Related Environmental Application: A Comprehensive Review and Perspectives. *ACS Environmental Au*, *5*(1), 35–60. doi: 10.1021/acsenvironau.4c00088

Karaiskakis, A. N., & Biddinger, E. J. (2017). Controllable Product Selectivity on Polycrystalline Cu through Tunable Surface Morphology. *ECS Meeting Abstracts*, *MA2017-02*(45), 2000–2000. doi: 10.1149/MA2017-02/45/2000

Kiamehr, Z., Shafiee, M., & Shokri, B. (n.d.). *Improving physico-chemical properties and antifouling of nanofiltration membranes using coating DLC nanostructures*.

Komal, & Awasthi, S. (2025). Advances in cellulose/graphene oxide-based polymer composites as a versatile platform for the diminution of water toxicants. *Journal of Molecular Liquids*, *426*. doi: 10.1016/j.molliq.2025.127261

Kujawa, J., Cerneaux, S., Koter, S., & Kujawski, W. (2014). Highly Efficient Hydrophobic Titania Ceramic Membranes for Water Desalination. *ACS Applied Materials & Interfaces*, *6*(16), 14223–14230. doi: 10.1021/am5035297

Kujawa, J., Cerneaux, S., Kujawski, W., & Knozowska, K. (2017). Hydrophobic Ceramic Membranes for Water Desalination. *Applied Sciences*, *7*(4), 402. doi: 10.3390/app7040402

Lakhotia, S. R., Mukhopadhyay, M., & Kumari, P. (2018). Surface-Modified Nanocomposite Membranes. *Separation & Purification Reviews*, *47*(4), 288–305. doi: 10.1080/15422119.2017.1386681

Liu, T., Chen, D., Yang, F., Chen, J., Cao, Y., Xiang, M., Kang, J., & Xu, R. (2019). Enhancing the permeability and anti-fouling properties of a polyamide thin-film composite reverse osmosis membrane *via* surface grafting of <scp>l</scp> -lysine. *RSC Advances*, *9*(35), 20044–20052. doi: 10.1039/C9RA02773D

Mataram, A., Nukman, Nasution, J. D., Riadi, M. I., Pataras, M., Aditya, B. B., Septano, G. D., Anisya, N., & Nadiyah, N. A. (2021). Comparison of Physical and Mechanical Properties of Antifouling PVDF Membranes by Titanium Dioxide and PES Membrane by Titanium Dioxide. *IOP Conference Series: Materials Science and Engineering*, *1041*(1), 012061. doi: 10.1088/1757-899X/1041/1/012061

Melanie, H., Anita, Y., Aspiyanto, Susilowati, A., Maryati, Y., Mulyani, H., & Budiari, S. (2022). *Partial purification of peroxidase from kailan (Brassica oleraceae var Alboglabra) by micro- and ultrafiltration membrane*. 040016. doi: 10.1063/5.0109924

Meng, S., Zhang, M., Yao, M., Qiu, Z., Hong, Y., Lan, W., Xia, H., & Jin, X. (2019). Membrane Fouling and Performance of Flat Ceramic Membranes in the Application of Drinking Water Purification. *Water*, *11*(12), 2606. doi: 10.3390/w11122606

Moinuddin, M., Biswas, P., & Tripathy, M. (2020). The effect of surface roughness on the phase behavior of colloidal particles. *The Journal of Chemical Physics*, *152*(4). doi: 10.1063/1.5136080

Mora, F., Pérez, K., Quezada, C., Herrera, C., Cassano, A., & Ruby-Figueroa, R. (2019). Impact of Membrane Pore Size on the Clarification Performance of Grape Marc Extract by Microfiltration. *Membranes*, *9*(11), 146. doi: 10.3390/membranes9110146

Nayak, D. T., Raja, V. K., Arthanareeswaran, G., Khoa, T. D., & Taweepreda, W. (2025). A high-performance nanofiltration membrane synthesized by embedding amino acids and ionic liquids in cellulose acetate for heavy metal separation. *RSC Sustainability*, *3*(4), 1966–

1981. doi: 10.1039/d4su00688g

Ngo, T. H. A., Nguyen, C. T. M., Do, K. D., Duong, Q. X., Tran, N. H., Nguyen, H. T. V., & Tran, D. T. (2020). Improvement of Hydrophilicity for Polyamide Composite Membrane by Incorporation of Graphene Oxide-Titanium Dioxide Nanoparticles. *Journal of Analytical Methods in Chemistry*, *2020*, 1–8. doi: 10.1155/2020/6641225

Omar, J. M., Nor, M. Z. M., Basri, M. S. M., & Che Pa, N. F. (2020). Clarification of guava juice by an ultrafiltration process: analysis on the operating pressure, membrane fouling and juice qualities. *Food Research*, *4*(S1), 85–92. doi: 10.26656/fr.2017.4(S1).S30

Rojjanapinun, A., & Pagsuyoin, S. A. (2021). Rice husk ash and Zr-MOF nanoparticles improve the properties and ultrafiltration performance of PVDF nanomembranes. *Results in Materials*, *12*. doi: 10.1016/j.rinma.2021.100234

Samanta, N. S., Mondal, P., & Purkait, M. K. (2023). Nanofiltration Technique for the Treatment of Industrial Wastewater. In Advanced Application of Nanotechnology to Industrial Wastewater (pp. 165–190). Singapore: Springer Nature Singapore. doi: 10.1007/978-981-99-3292-4_9

Santos, J. A. L., Mateus, M., & Cabral, J. M. S. (1991). Pressure Driven Membrane Processes. In Chromatographic and Membrane Processes in Biotechnology (pp. 177–205). Dordrecht: Springer Netherlands. doi: 10.1007/978-94-011-3470-5_9

Sarkar, P., Modak, S., & Karan, S. (2021). Ultraselective and Highly Permeable Polyamide Nanofilms for Ionic and Molecular Nanofiltration. *Advanced Functional Materials*, *31*(3). doi: 10.1002/adfm.202007054

Senthil Muthu Kumar, T., Senthilkumar, K., Ratanit, M., Rajini, N., Chanunpanich, N., Hariram, N., Pornwongthong, P., & Siengchin, S. (2021). Influence of Titanium Dioxide Particles on the Filtration of 1,4-Dioxane and Antibacterial Properties of Electrospun Cellulose Acetate and Polyvinylidene Fluoride Nanofibrous Membranes. *Journal of Polymers and the Environment*, *29*(3), 775–784. doi: 10.1007/s10924-020-01919-0

Shahid, M. U., Najam, T., Islam, M., Hassan, A. M., Assiri, M. A., Rauf, A., Rehman, A. ur, Shah, S. S. A., & Nazir, M. A. (2024). Engineering of metal organic framework (MOF) membrane for waste water treatment: Synthesis, applications and future challenges. In Journal of Water Process Engineering (Vol. 57). Elsevier Ltd. doi: 10.1016/j.jwpe.2023.104676

Sharma, S., Dhingra, P., & Jain, S. (2023). Advancements & challenges of nanotechnology in waste water treatment. *Materials Today: Proceedings*, *80*, 18–23. doi: 10.1016/j.matpr.2022.09.481

Siddiqui, M., Arif, A., & Bashmal, S. (2016). Permeability-Selectivity Analysis of Microfiltration and Ultrafiltration Membranes: Effect of Pore Size and Shape Distribution and Membrane Stretching. *Membranes*, *6*(3), 40. doi: 10.3390/membranes6030040

Sun, S., Shan, F., Lyu, Q., Li, C., & Hu, S. (2019). Theoretical Prediction of Mechanical Strength and Desalination Performance of One-Atom-Thick Hydrocarbon Polymer in Pressure-Driven Separation. *Polymers*, *11*(8), 1358. doi: 10.3390/polym11081358

Tang, N. F. R., Armynah, B., & Tahir, D. (2024). Structural and optical properties of alginate-based antibacterial dressing with calcium phosphate and zinc oxide for biodegradable wound painting applications. *International Journal of Biological Macromolecules*, *276*. doi: 10.1016/j.ijbiomac.2024.133996

Tang, N. F. R., Tahir, D., & Heryanto, H. (2022). Sintesis Komposit ZnO/Ca3(PO4)2 menggunakan metode

Sol-gel sebagai Material Fotokatalis Limbah Cair Industri (Metilen Biru). *Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat*, *19*(1), 31. doi: 10.20527/flux.v19i1.11824

Tanne, N., Xu, R., Zhou, M., Zhang, P., Wang, X., & Wen, X. (2019). Influence of pore size and membrane surface properties on arsenic removal by nanofiltration membranes. *Frontiers of Environmental Science & Engineering*, *13*(2), 19. doi: 10.1007/s11783-019-1105-8

Tripathy, D. B. (2024). Recent advances on 2D Metal Organic Framework (MOF) membrane for waste water treatment and desalination. In Desalination (Vol. 592). Elsevier B.V. doi: 10.1016/j.desal.2024.118183

Wang, M., Li, L., Yan, H., Liu, X., Li, K., Li, Y., You, Y., Yang, X., Song, H., & Wang, P. (2023). Poly(arylene ether)s-Based Polymeric Membranes Applied for Water Purification in Harsh Environment Conditions: A Mini-Review. *Polymers*, *15*(23), 4527. doi: 10.3390/polym15234527

Warsinger, D. M., Chakraborty, S., Tow, E. W., Plumlee, M. H., Bellona, C., Loutatidou, S., Karimi, L., Mikelonis, A. M., Achilli, A., Ghassemi, A., Padhye, L. P., Snyder, S. A., Curcio, S., Vecitis, C. D., Arafat, H. A., & Lienhard, J. H. (2018). A review of polymeric membranes and processes for potable water reuse. *Progress in Polymer Science*, *81*, 209–237. doi: 10.1016/j.progpolymsci.2018.01.004

Wei, Y., Qi, H., Gong, X., & Zhao, S. (2018). Specially Wettable Membranes for Oil–Water Separation. *Advanced Materials Interfaces*, *5*(23). doi: 10.1002/admi.201800576

Wu, J., Zhou, H., Wang, H., Shao, H., Yan, G., & Lin, T. (2019). Novel Water Harvesting Fibrous Membranes with Directional Water Transport Capability. *Advanced Materials Interfaces*, *6*(5). doi: 10.1002/admi.201801529

Xiong, Z., He, Z., Mahmud, S., Yang, Y., Zhou, L., Hu, C., & Zhao, S. (2020). Simple Amphoteric Charge Strategy to Reinforce Superhydrophilic Polyvinylidene Fluoride Membrane for Highly Efficient Separation of Various Surfactant-Stabilized Oil-in-Water Emulsions. *ACS Applied Materials & Interfaces*, *12*(41), 47018–47028. doi: 10.1021/acsami.0c13508

Yang, Z., Zhou, Y., Feng, Z., Rui, X., Zhang, T., & Zhang, Z. (2019). A Review on Reverse Osmosis and Nanofiltration Membranes for Water Purification. *Polymers*, *11*(8), 1252. doi: 10.3390/polym11081252

Yu, Y., Xue, Y., Zhao, J., Ning, K., & Sun, S. (2025). CNTs-COOH@TA nanoparticles and chitosan hydrogel regulated PVDF composite fiber membranes with efficient oil-in-water emulsion and dye wastewater separation characters. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *718*. doi: 10.1016/j.colsurfa.2025.136905

Yue, C., Dong, H., Chen, Y., Shang, B., Wang, Y., Wang, S., & Zhu, Z. (2021). Direct Purification of Digestate Using Ultrafiltration Membranes: Influence of Pore Size on Filtration Behavior and Fouling Characteristics. *Membranes*, *11*(3), 179. doi: 10.3390/membranes11030179

Yuliati Jurusan Teknik Kimia Politeknik negeri Sriwijaya, S., Negeri Sriwijaya, P., & Srijaya Negara Bukit Besar, J. (n.d.). *PENGOLAHAN AIR MENGGUNAKAN MEMBRAN ULTRAFILTRASI SEBAGAI UPAYA MENDUKUNG GERAKAN NASIONAL MENGATASI KRISIS AIR BERSIH*.

Zhang, L. Q., & Zhang, G. (2013). Influence of Membrane Structure and Chemical Characteristics on Separation and Fouling of Nanofiltration Membranes. *Advanced Materials Research*, *864–867*, 394–398. doi: 10.4028/www.scientific.net/AMR.864-867.394

Zhang, L., Qin, L., Ma, L., Shen, Z., Jin, Y., & Chen, S. (2024). Treatment of electroplating wastewater using electrocoagulation and integrated membrane. *Water Science & Technology*, *89*(9), 2538–2557. doi: 10.2166/wst.2024.136

Zhao, Y., Qin, Z., Zhao, Y., Cui, S., & Guo, H. (2019). Evaluating the anti-fouling property of the hydrophilically modified porous PTFE membrane. *Desalination and Water Treatment*, *159*, 224–231. doi: 10.5004/dwt.2019.24257

Zhu, B., Duke, M., Dumée, L. F., Merenda, A., Des Ligneris, E., Kong, L., Hodgson, P. D., & Gray, S. (2018). Short Review on Porous Metal Membranes—Fabrication, Commercial Products, and Applications. *Membranes*, *8*(3), 83. doi: 10.3390/membranes8030083

Zulkefli, N. F., Alias, N. H., Jamaluddin, N. S., Abdullah, N., Abdul Manaf, S. F., Othman, N. H., Marpani, F., Mat-Shayuti, M. S., & Kusworo, T. D. (2021). Recent Mitigation Strategies on Membrane Fouling for Oily Wastewater Treatment. *Membranes*, *12*(1), 26. doi: 10.3390/membranes12010026