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Kafle, Saroj Raj

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Advancement of membrane separation technology for organic pollutant removal

Saroj Raj Kafle[a,†], Sangeet Adhikari[b,†], Rakesh Shrestha[c], Sagar Ban[c], Gaurav Khatiwada[c], Pragati Gaire[c], Nerisha Tuladhar[c], Guangming Jiang[d] and Ananda Tiwari[e,f,*,†]

[a] Department of Chemical Engineering, Texas A&M University, College Station, TX, USA
[b] School of Sustainable Engineering and the Built Environment, Tempe, AZ 85281, USA
[c] Department of Chemical Science and Engineering, Kathmandu University, P.O. BOX 6250, Dhulikhel, Kavre, Nepal
[d] School of Civil, Mining, and Environmental Engineering, University of Wollongong, Wollongong, Australia
[e] University of Helsinki, Faculty of Veterinary Medicine, Department of Food Hygiene and Environmental Health, Agnes Sjöbergin katu 2, Helsinki FI-00014, Finland
[f] Department of Health Security, Water Microbiology laboratory, Finnish Institute for Health and Welfare, Kuopio, Finland
*Corresponding author. E-mail: ananda.tiwari@thl.fi
†Equally contributed to this work.

AT, 0000-0001-8026-6885

ABSTRACT

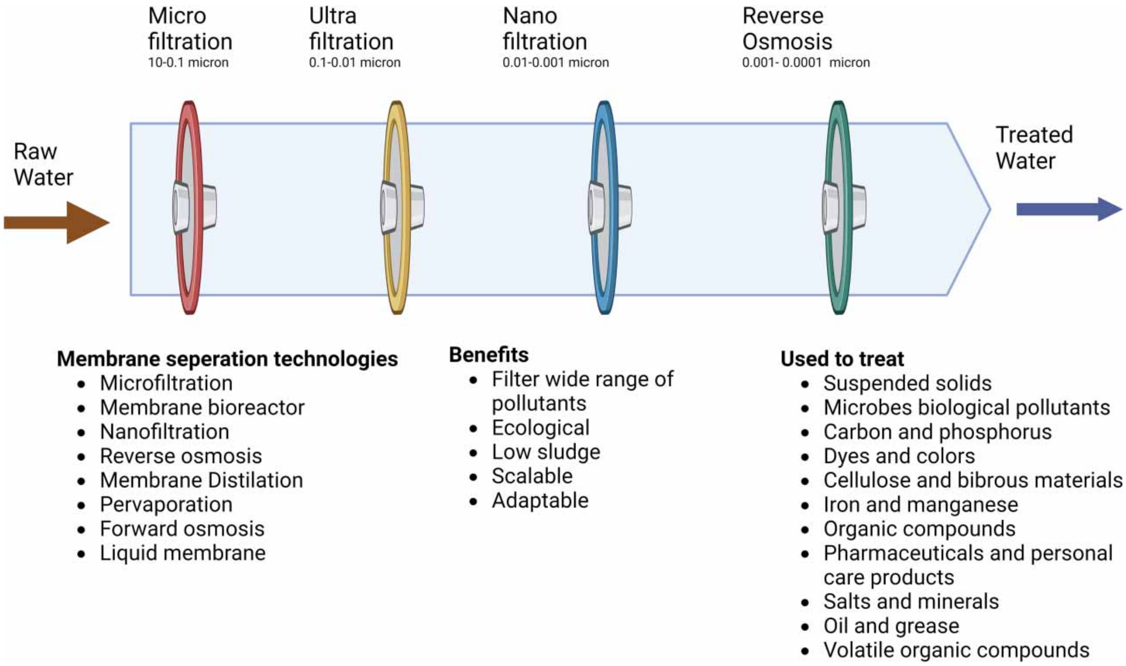
In the face of growing global freshwater scarcity, the imperative to recycle and reuse water becomes increasingly apparent across industrial, agricultural, and domestic sectors. Eliminating a range of organic pollutants in wastewater, from pesticides to industrial byproducts, presents a formidable challenge. Among the potential solutions, membrane technologies emerge as promising contenders for treating diverse organic contaminants from industrial, agricultural, and household origins. This paper explores cutting-edge membrane-based approaches, including reverse osmosis, nanofiltration, ultrafiltration, microfiltration, gas separation membranes, and pervaporation. Each technology's efficacy in removing distinct organic pollutants while producing purified water is scrutinized. This review delves into membrane fouling, discussing its influencing factors and preventative strategies. It sheds light on the merits, limitations, and prospects of these various membrane techniques, contributing to the advancement of wastewater treatment. It advocates for future research in membrane technology with a focus on fouling control and the development of energy-efficient devices. Interdisciplinary collaboration among researchers, engineers, policymakers, and industry players is vital for shaping water purification innovation. Ongoing research and collaboration position us to fulfill the promise of accessible, clean water for all.

Key words: fouling mechanisms, membrane technologies, organic contaminant removal, wastewater treatment

HIGHLIGHTS

- Effective wastewater treatment helps to recycle and reuse water.
- Membrane technologies are promising for treating wide organic contaminants.
- This paper explores various advanced membrane techniques.
- This review examines membrane fouling, including influencing factors and prevention strategies.
- It illuminates the evolving membrane techniques, aiding the progress of wastewater treatment.

GRAPHICAL ABSTRACT



ABBREVIATIONS

AMD	acid mine drainage system
BLM	bulk liquid membrane
CA	cellulose acetate
CNC	cellulose nanocrystal
COD	chemical oxygen demand
CTA	cellulose triacetate
DCMD	direct contact membrane distillation
DMF	dimethylformamide
DMSO	dimethyl sulfoxide
EGDMA	ethylene glycol dimethylcrylate
ELM	emulsion liquid membrane
EPS	extracellular polymeric substances
FO	forward osmosis
FOMBR	forward osmosis membrane reactor
FOwEO	forward osmosis with the function of electrochemical oxidation
FTIR	Fourier transformation infrared spectroscopy
GO	graphene oxide
IBU	Ibuprofen
LAS	linear alkylbenzene
LM	liquid membrane
MBR	membrane bioreactor
MCE	mixed cellulose ester
MDP	m-phenylenediamine
MF	microfiltration
NF	nanofiltration
NMP	N-methyl pyrrolidone
OSRO	reverse osmosis organic solvent
PA	polyamide
PAFO	pressure-assisted forward osmosis
Pd	palladium
PDMS	polydimethylsiloxane

PE	polyethylene
PEGDA	polyethylene glycol diacrylate
PEI	polyethyleneimine
PES	polyether sulfone
PK	polyketone
PV	pervaporation
PVDF	polyvinylidene
RSF	reverse salt flux
RSM	response surface methodology
RO	reverse osmosis
SA	salicylic acid
SGMD	sweep gas membrane distillation
SLM	supported liquid membrane
SRSF	specific reverse salt flux
TBP	tributyl phosphate
TDA	tridodecylamine
TDS	total dissolved solids
TFC	thin film composite
TFN	thin-film nanocomposites
TOC	total organic carbon
TrOC	trace organic compound
TSS	total suspended solids
WWTP	wastewater treatment plant
XRD	X-ray diffraction

1. INTRODUCTION

Membrane separation technology (MST) is promising for selectively removing various organic pollutants from diverse sources through a semi-permeable membrane (Nqombolo *et al.* 2018; Obotey Ezugbe & Rathilal 2020; Bera *et al.* 2022). This technology is promising for removing a range of physical, biological, and chemical pollutants. It serves as a cost-effective and ecological wastewater treatment solution, notable for its minimal chemical usage and absence of hazardous byproducts (Jacangelo *et al.* 1997). Consequently, MST contributes to safeguarding public health and the environment by reducing exposure to harmful organic pollutants (Guo *et al.* 2019).

Selecting an appropriate membrane type, influenced by pollutant size properties and wastewater characteristics, is the primary step in MST for removing organic pollutants (Lee *et al.* 2016; Dai *et al.* 2019; Subramaniam *et al.* 2019; Ahmed *et al.* 2021; Ren *et al.* 2021; Rout *et al.* 2021). For instance, a hydrophobic membrane can effectively remove biocides and bacterial organic particles (Shahid *et al.* 2021). This technology provides an economical, sustainable, and efficient wastewater treatment method. It produces low sludge, is eco-friendly, scalable, adaptable to different environments, and can be integrated with other treatment methods for enhanced efficiency (Singh & Hankins 2016). It is scalable, adaptable to various environments, and can be integrated with other treatment methods to enhance removal efficiency.

Various organic pollutants, such as volatile organic compounds (VOCs) – including gaseous or liquid-phase compounds such as solvents, chemical precursors, intermediates, and petroleum compounds – can be present in wastewater. These substances are typically released from solvents, fuels, and other chemicals. Similarly, polycyclic aromatic hydrocarbons, another type of organic pollutant, form through the incomplete combustion of materials such as coal, oil, and gas. Another category of organic pollutants in wastewater is pharmaceuticals and personal care products (PPCPs). These include commonly used substances such as antibiotics, hormones, and fragrances, which enter wastewater through urine and feces (Gaur *et al.* 2018). PPCPs, including substances such as antibiotics, hormones, and fragrances used in daily life, can end up in wastewater through urine and feces. Pesticides, utilized in agriculture for pest and disease control, can be released into the environment via runoff, leaching, and spray drift (Wolf *et al.* 1991). Similarly, chlorinated solvents, used in industrial processes such as dry cleaning and metal cleaning, can enter the environment through spills, leaks, and improper disposal. Dioxins and furans, toxic byproducts of certain industrial processes such as waste incineration and chemical manufacturing, can also form during forest fires and volcanic eruptions. Proper wastewater treatment processes are essential to mitigate the adverse effects of these pollutants and protect both human health and the environment (Garcia-Rodríguez *et al.* 2014).

Various membrane types, including polymeric, ceramic, and composite membranes, have been evaluated for their potential to remove organic pollutants to advance membrane bioreactors (MBRs), forward osmosis (FO), and other applications (Warsinger *et al.* 2018). However, a comprehensive understating of the removal of organic contaminants, and their complex interactions with membrane materials and the surrounding environment is lacking (Khan & Ghoshal 2000; Farahbakhsh *et al.* 2004; Huang *et al.* 2009; Li & Visvanathan 2017; Malkoske *et al.* 2020). These limitations pose challenges in scaling up MST from laboratory scale to practical applications. While attempts have been made to optimize these limitations, studies conducted in diverse settings with different pollutants and conditions make it challenging to draw concrete comparisons (Lee *et al.* 2016; Dai *et al.* 2019; Subramaniam *et al.* 2019; Ahmed *et al.* 2021; Ren *et al.* 2021; Rout *et al.* 2021). The next significant challenge in this field is addressing fouling and membrane degradation to broaden the utilization of MST (Sayan *et al.* 2013).

Previous MST research for organic pollutant removal primarily aimed at optimizing membrane selectivity and permeability (Yang & Yang 2022), optimizing operating conditions to enhance separation efficiency (Gan *et al.* 2023), and understanding pollutant transport mechanisms through membranes (Ren *et al.* 2021). Additional studies explored the application of nanofiltration and reverse osmosis (RO) membranes to eliminate pharmaceuticals and endocrine disruptors (Riley *et al.* 2016). Research also delved into developing hybrid membrane systems for treating oil and gas-produced water and utilizing MBRs for industrial wastewater treatment (Riley *et al.* 2016).

Organic pollutants can be separated through physical, biological, or chemical processes. Physical separation can be a better option among these, especially when compared to biological degradation, which can be complex due to the potential toxicity of organic pollutants (Hanafi & Sapawe 2020). While chemical processing could be a viable alternative, offering a solution for eliminating organic and inorganic matter, color, and recalcitrant substances, it can be more expensive and falls beyond the scope of the current study (Hanafi & Sapawe 2020). This study aims to (a) evaluate the effectiveness of various membrane technologies for removing organic pollutants removal, identifying their respective advantages and limitations, (b) investigate novel pre-treatment methods to minimize fouling, enhance membrane durability, and devise strategies for improving membrane selectivity towards specific organic pollutants while maintaining high permeability. The insights gained from this review can aid researchers and engineers in developing membrane-based treatment systems, effectively eliminating organic pollutants from diverse wastewater types and contributing to environmental protection.

2. MEMBRANE TECHNOLOGY TYPES

In recent decades, various physical separation-based MSTs have gained popularity for their advantages in water and wastewater treatment (Quist-Jensen *et al.* 2015). However, membrane fouling remains a challenge despite these benefits, especially with highly soluble contaminants. This chapter deals with the various physical separation MSTs, emphasizing their applications and challenges.

2.1. Microfiltration

Microfiltration (MF) is widely used in diverse industries such as pharmaceuticals, food and beverages, and semiconductors, for effective wastewater treatment (Baker 2012). This process uses filter pore sizes from 0.1 to 10 μm to eliminate pollutants such as sediment, algae, protozoa, bacteria, and proteins (Baker 2012). However, MF cannot remove tiny colloids, viruses, natural organic matter, and ions that surpass its filter retention capabilities (Howe *et al.* 2012).

Membrane materials in MF are selected for high mechanical strength, film-forming properties, good thermal and chemical stability, and stability over a wide pH range (Urošević & Trivunac 2020; Gul *et al.* 2021). Notably, a cementitious membrane effectively removes small organic pollutants, showcasing a significantly improved reaction rate constant compared to standalone ozone oxidation. Additionally, the membrane demonstrates good retention efficiency at low trans-membrane pressure (Sun *et al.* 2021).

MF transports suspended liquids through a sheet or tubular configuration, either parallel or perpendicular to the semi-permeable membrane (Figure S1). This process occurs at reasonably high velocities, typically in the 1–3 m/s range, and under low to moderate pressures, usually around 100–400 kPa (Green & Southard 2019). A pump, either vacuum-driven or pressure-driven, serves as the processing equipment, facilitating the liquid flow through the membrane filter. To monitor the pressure differential between the inlet and outlet streams, a differential or standard pressure gauge is frequently installed (Baker 2012).

Hybrid systems, such as integrating photocatalysis and membrane MF functionalities, reduce membrane fouling and enhance permeate flux, reporting efficiency increases of up to 10% (Ho *et al.* 2010; Zhao *et al.* 2020). Another noteworthy hybrid system combines MF with biological treatment using a mixed cellulose ester membrane, effectively resulting chemical oxygen demand (COD), total organic carbon (TOC), and phenols (Mameda *et al.* 2020). Furthermore, electrochemical MF is effective in removing COD, nitrogen, organic carbon, color, turbidity, and fluorophores (Mameda *et al.* 2020). In a separate development, a reactor combining electro-oxidation with a boron-doped diamond (BDD)/Ti anode and ceramic membrane MF was created to simultaneously remove soluble and particulate organic matter from wastewater, achieving complete COD removal and 90% removal of color and turbidity from dye wastewater (Juang *et al.* 2013).

MF is a potent wastewater treatment method, yet certain limitations merit consideration (Table 1). Common drawbacks include fouling, susceptibility under harsh chemical, thermal, or mechanical conditions, and relatively low durability. Moreover, MF can be costly due to three major factors: sintering temperature, membrane materials, and preparation procedures. Reducing the cost of MF is an important but challenging, as altering sintering temperature and preparation procedures may prove difficult. However, developing cost-effective raw materials for membranes can help mitigate overall costs (Singh & Purkait 2019).

2.2. Membrane bioreactor

MBR is an emerging wastewater treatment technology utilizing low-pressure membrane filtration to separate effluent from activated sludge (Jefferson *et al.* 2000). This approach combines a biological wastewater treatment process, such as the activated sludge process, with a membrane process, including MF or ultrafiltration (Figure S2). MBR has two primary configurations: the submerged membrane bioreactor (SMBR) and the side-stream MBR (Goswami *et al.* 2018). In SMBRs, the membrane is within the biological reactor and submerged in the wastewater, while in the side-stream MBR, the membrane is positioned outside the reactor as an additional step following biological treatment (Goswami *et al.* 2018).

In an MBR system, membranes with pore sizes between 0.035 and 0.4 μm are immersed in an aerated biological reactor (van't Oever 2005). This eliminates the need for sedimentation and filtration processes common in wastewater treatment, enabling the biological process to operate at a higher mixed liquor concentration, thereby reducing the required process tankage. The mixed liquor is typically maintained at 1.0–1.2% solids, ensuring optimal aeration and scouring around the membranes, a concentration four times higher than conventional plants (van't Oever 2005).

Table 1 | Some applications of microfiltration (MF) membranes

Membrane material	Source of wastewater	Removal efficiency (%)	Membrane properties	Merits	Demerits	References
Electrodeposited CuO/carbon membrane (DECuO/C)	Laboratory analysis	RhB = 99.96; COD = 71.82; TOC = 64.29	Permeability = 823.03 L/(m^2·h·bar)	An approach to preparing high-performance electrocatalytic membrane	Pollutants smaller than membrane pores are difficult to remove	Li *et al.* (2020)
Integrated biological-ceramic membrane	Industries such as pulp and paper, biomass gasification, and dairy	COD (pulp and paper) = 92.7; COD (biomass gasification) = 87.6; COD (dairy) = 88.2	Porosity = 44%, pore diameter = 1 μm	Cost-effective approach		Goswami *et al.* (2019)
PVDF	Greywater	COD = 98.22; LAS = 99.97; TSS = 99.99; turbidity = 99.98	Pore size = 0.1 μm; membrane area = 0.2 m^2; membrane length = 50 cm	The combination of multi-layer slow sand filter, MF, and ultrafiltration is more effective for LAS and suspended solids	An increase in organic loading rates decreases the removal efficiency	Babaei *et al.* (2019)
Aluminosilicate composite	Laboratory analysis	Benzophenone-4 = 100; TOC = 52.67	Pore size = 1.33–0.15 μm	Low cost non-toxic, good mechanical strength with a large pore-size membrane material	Mechanical strength was affected by changes in different parameters	Sun *et al.* (2021)

COD = chemical oxygen demand, LAS = linear alkylbenzene, TSS = total suspended solids, TOC = total organic carbon.

MBR technology, with its clear advantages over conventional methods, has clear advantages over conventional methods, and it is widely used in diverse industrial wastewater treatment applications (Table 2). Employing membrane filtration units to replace the secondary settler provides several benefits compared to traditional approaches (Lin *et al.* 2012). This allows effective treatment of dense wastewater, including industrial effluents and landfill leachate (Van Dijk & Roncken 1997).

Comparative studies between MBRs and conventional activated sludge systems for micropollutant degradation reveal shorter lag phases and stronger memory effects in MBRs. This suggests a quicker response to variable influent concentrations and reduced sensitivity to operational variables (De Wever *et al.* 2007). In an experiment focusing on removing alkyl phenol ethoxylates and their degradation products, linear alkylbenzene (LAS) sulfonates, and coconut diethanol amides, an MBR was evaluated alongside a full-scale wastewater treatment plant employing conventional activated sludge (González *et al.* 2007). The MBR exhibited a 94% efficiency in retaining and degrading alkyl-phenolic compounds, contrasting with the conventional activated sludge treatment's 54% removal of total nonylphenol compounds (González *et al.* 2007).

In an experiment exploring mixed liquor pH impact (ranging from pH 5 to 9) on trace organics removal in a submerged MBR system, results showed notable pH-related effects on ionizable trace organics, such as sulfamethoxazole, ibuprofen, ketoprofen, and diclofenac. Higher removal efficiencies were evident at pH 5 due to enhanced adsorption to activated sludge (Tadkaew *et al.* 2010). A subsequent study examined the degradation of 3 estrogens, 2 endocrine disruptors, and 10 pharmaceutical substances in a membrane separation bioreactor. Lower pH operation correlated with increased removal rates of acidic pharmaceutical substances, primarily attributed to heightened adsorption to sludge particles (Urase *et al.* 2005).

Despite the numerous advantages of MBRs over conventional methods, membrane fouling poses a significant challenge, reducing productivity and increasing maintenance and operating costs. This fouling can manifest on the membrane surface or within the membrane pores, being reversible (removable by physical washing) or irreversible (requiring chemical cleaning). Researchers highlight extracellular polymeric substances (EPS), specifically the carbohydrate fraction from the soluble microbial product (soluble EPS or biomass supernatant), as a key fouling factor in MBRs. Various strategies, such as adjusting hydrodynamics and flux, optimizing module design, and manipulating bioreactor conditions, have been proposed to control fouling (Le-Clech *et al.* 2006).

2.3. Reverse osmosis

RO stands out as an advanced membrane filtration method that employs a semi-permeable membrane to effectively eliminate ions, molecules, larger particles, and various dissolved and suspended contaminants, including viruses (Ouyang *et al.* 2019). This process relies on applying pressure to counteract osmotic pressure (Figure S3), typically ranging from 17 to 27 bars for

Table 2 | Various applications of filtration membrane

Industry	Applications	References
Food and beverage	• Concentration and nutritional enrichments of food products • Control of alcohol content of wines partial sugar removal from musts • Reduction of volatile acidity in wines acidification of wines • Removal of phenolic compounds from pomegranate juice	Abdel-Fatah (2018), Mulyanti & Susanto (2018), Nath *et al.* (2018)
Textile and dyes	• Concentration • Permeation of organic salts • Removal of color • Removal of reactive dyes, salts, dye intermediates from wastewater	Abdel-Fatah (2018), Nath *et al.* (2018), Tavangar *et al.* (2019)
Industrial process and wastewater	• Remove wastewater and semi-volatile organic compound from industrial process • Removal of degreasing agents from wastewater • Removal of organic pollutants such as pesticides	Abdel-Fatah (2018), Nath *et al.* (2018)
Biotech and pharmaceuticals	• Separation, concentration, recovery, and production of hormones	Abdel-Fatah (2018), Kyburz *et al.* (2021)

brackish water and 52 to 69 bars for seawater. Osmotic pressure, a colligative property driven by differences in the chemical potential of the solvent (Table 3), propels this mechanism. Diffusion serves as the primary force for organic liquid separation and overcoming the formidable osmotic pressure barrier (Liu *et al.* 2021a).

Effectively separating molecules smaller than 100 Da poses a considerable challenge, especially in pursuing an energy-efficient membrane technology for organic molecule separation. The swelling issue is significant in RO separation, particularly when dealing with organic solvents with a molecular weight below 100 Da.

In general, chemically and thermally stable cellulose is extracted from plants, while living organisms are employed in RO (Abdel-Fatah 2018). Improving the anti-fouling properties of the RO cellulose membrane involved incorporating cellulose nanocrystals into the polyamide (PA) thin-film nanocomposites membrane through in-situ polymerization of m-phenylenediamine and trimethyl chloride. This enhancement was confirmed through X-ray diffraction and Fourier transformation infrared spectroscopy analysis (Asempour *et al.* 2018).

For the separation of methanol and isobutanol from wastewater, a uniform cellulose membrane exhibited higher adsorption of methanol compared to isobutanol (Liu *et al.* 2021a). A cellulose acetate (CA)/graphene oxide (GO) nanocomposite membrane was prepared using the plane inversion method. Increasing the GO concentration up to 1 wt.% improved mechanical properties due to physiochemical interactions with the CA matrix. However, a further increase in concentration adversely affected membrane separation (Ghaseminezhad *et al.* 2019).

A subsequent study evaluated the removal efficiency of ultra-trace organic compounds (TrOCs) by a hollow fiber cellulose triacetate (CTA) RO membrane. The reported removal efficiency was similar to that of PA membranes, with molecular size significantly influencing the removal process (Fujioka *et al.* 2015).

A reverse osmosis organic solvent (OSRO) membrane was developed through interfacial polymerization on a polyketone (PK) support, achieved separation factor of 8.4 for methanol from the methanol/toluene mixture. To enhance selectivity and the separation factors, the simple heat treatment process, including initial oven heating followed by hot water heating, was applied (Liu *et al.* 2021b). Coating an organic-resistant substance on the PK support using a straightforward procedure resulted in an OSRO membrane with a flux of 1.0–4.0 km for non-polar liquids (alkane and toluene) and zero flux for polar liquids (alcohol) under 4 MPa (Liu *et al.* 2021b).

Utilizing a polyethylene (PE) support, a highly selective and mechanically durable PA thin-film composite (TFC) reverse osmosis (RO) membrane was prepared. The TCE-PE membrane exhibited superior mechanical and organic solvent resistance properties compared to commercial membranes (Park *et al.* 2018). Benzyl alcohol (BA) enhanced the separation performance of PA RO membranes, with BA-activated RO membranes showing higher water performance and perm selectivity than commercial membranes (Shin *et al.* 2019).

Silica significantly improved the properties of polyethylene glycol membranes in RO, improving both hydrophilicity and fouling resistance (Ahmad *et al.* 2015). After activating various concentrations of polyethylene glycol diacrylate and ethylene glycol dimethacrylate with sodium hypochlorite for 1 h, a TFC-RO membrane with high performance, and lower organic fouling was prepared (Kavaiya & Raval 2022). Addressing the challenging removal of boron from seawater, Uio-66 nanoparticles were doped into a PA thin-film nanocomposite RO membrane. This doping improved boron rejection by 11% compared to benchmark membranes (Liu *et al.* 2019).

While RO offers numerous advantages over other membrane techniques, it is essential to consider major drawbacks such as low permeation flux, inadequate selectivity, limited membrane durability, membrane fouling, and high equipment and

Table 3 | Estimated osmotic pressures for various organic solvent

Organic liquid name	Estimated osmotic pressure (bar)
NMP/Toluene	21.93
DMF/Toluene	29.63
DMSO/Toluene	27.99
DMSO/Toluene	26.31
NMP/Methanol	20.26

NMP = N-methyl pyrrolidone, DMF = dimethylformamide, DMSO = dimethyl sulfoxide.

operational costs (Wenten 2016). Addressing these challenges involves combining co-solvent interfacial polymerization and surface modification of substrates and active layers in RO membranes (Hailemariam *et al.* 2020).

2.4. Nanofiltration

Nanofiltration, an advanced membrane technology, is used for water and wastewater treatment and efficient recovery of divalent metals (Butterworth 2010). This technique utilizes a semi-permeable organic membrane under pressure to separate substances. The membranes have ultra-small pores, typically ranging from 0.1 to 10 nm, often around 1 to 2 nm in size, and with a molecular weight range of 100–5,000 Da (Nath 2017).

Nanofiltration membranes represent a versatile separation technology with properties lying between those of ultrafiltration and RO membranes (Figure S4). The separation process in nanofiltration hinges on differences in particle size and charge effects, particularly for ionic components (Mulyanti & Susanto 2018). Physical sieving emerges as a dominant mechanism for components with high molecular weight (Shon *et al.* 2013).

Nanofiltration membranes can be produced through polymer phase inversion, resulting in uniform asymmetric membranes, or via interfacial polymerization, where a TFC layer is added to an ultrafiltration membrane substrate (Table 4). Common materials for homogeneous asymmetric nanofiltration membranes include CA and sulfonated polysulfone. TFC nanofiltration membranes utilize cross-linked PA polymers with charged 'pendants,' and typical substrate materials include polysulfone, polyether sulfone (PES), polyvinylidene fluoride (PVDF), polyacrylonitrile, and polyether ether ketone.

To withstand extreme conditions such as low or high pH, high temperatures, or organic solvent environments, highly cross-linked nanofiltration membranes have been developed, featuring a slightly charged surface (Van der Merwe 1998). Key characteristics include low rejection of monovalent ions, high rejection of divalent ions, and high flux when compared to ultrafiltration and RO membranes (Marchetti *et al.* 2014; Mohammad *et al.* 2015).

In a previous study, the diffusion phenomenon was evaluated through molecular dynamic simulation of eight monosaccharides. The study found that the interaction force between the membrane and monosaccharides followed the order of sorbose > fructose > glucose > mannose > galactose, and ribose > xylose > arabinose. Additionally, the diffusion coefficient of the monosaccharides inside the membrane was found to be in the order sorbose > galactose > glucose > mannose > fructose > ribose > xylose > arabinose (Yao *et al.* 2018). Membrane performances are significantly influenced by operating conditions such as temperature, operating pressure, flow rate, membrane characteristics, and feed characteristics (Mulyanti & Susanto 2018).

Table 4 | Common membrane types used in nanofiltration

Membrane	Efficiency	Drawbacks	Advantage	Reference
Polymeric membrane	High	Limited thermal and solvent stability	• Cost-effectiveness, excellent process ability, good reproducibility, and versatility	Lim *et al.* (2017)
Cellulose-based membrane	High	Shorter life span, low resistance to membrane fouling, low chemical resistance, weak high-temperature resistance	• High strength, high specific surface area, high surface activity, non-toxic, renewable	Liu *et al.* (2021c)
TFC membrane	High	Impossible for large-scale production, high cost	• High yield • Energy efficient • High selectivity • High water permeability	Voicu & Thakur (2021); Seah *et al.* (2020)
Ceramic membrane	Medium	Inflexible, high investment cost, low degradability, less selectivity, high energy consumption	• High thermal stability • High chemical resistant • High pressure • Long life • Less contaminated	Liu *et al.* (2021c)
Metallic oxide membrane	Medium	High raw material cost	• High water permeability • More effective for removing bacterial particles	Yang *et al.* (2019); Sonawane *et al.* (2021)

Fouling is a significant challenge in the nanofiltration process, resulting in decreased flux and diminished cost efficiency over time. It arises from various soluble and suspended materials, including colloids, organic and inorganic substances, as well as biological components (Mohammad *et al.* 2015). To mitigate fouling, various physical, chemical, and hydrodynamic methods can be employed (Table 6). Notably, the acid mine drainage (AMD) system has proven effective in removing organic fouling in nanofiltration membranes, with hydrochloric acid (HCl) solutions being particularly efficient in addressing AMD-related fouling issues (Juholin *et al.* 2018). The utilization of graphene-based membranes and the incorporation of nanomaterials shown significant promise in reducing membrane fouling in organic nanofiltration processes (Nie *et al.* 2021). However, further studies are needed for even more efficient and effective fouling control (Mohammad *et al.* 2015).

2.5. Membrane distillation

Membrane distillation (MD) is a promising, thermally driven separation technology utilizing a porous hydrophobic membrane that allows passing of vapor molecules (Figure S5). The pressure difference across the membrane surfaces serves as the driving force (A Shirazi & Kargari 2015). MD is applied in diverse fields, including desalination of both seawater and brackish water, treating radioactive waste, and removing organics and heavy metals from wastewater (Alkhudhiri *et al.* 2012). The MD process encompasses four configurations: direct contact membrane distillation (DCMD), air gap MD, vacuum MD, and sweep gas MD. Notably, DCMD, the most common configuration, is applied in various wastewater treatment applications targeting organic pollutants (Curcio & Drioli 2005).

Unlike conventional thermal distillation, MD operates at a lower temperature, driven by a non-exclusively thermal force. The hydrophobic membrane prevents the entry of aqueous solutions into pores, establishing liquid/vapor interfaces only under a trans-membrane pressure surpassing the membrane's liquid entry pressure. Consequently, three stages define water transport through the membrane: (1) formation of a vapor gap at the interface between the hot feed solution and the membrane, (2) transportation of the vapor phase through the microporous system, and (3) condensation of vapor at the interface between the cold side of the membrane and the permeate solution (Onsekizoglu 2012).

The MD process offers significant advantages, operating at lower temperatures than conventional methods and requiring lower hydrostatic pressure than pressure-driven technologies, enhancing cost-effectiveness. MD, a relatively new and energy-efficient process, stands out for its lower operational costs and energy consumption compared to conventional techniques such as distillation and RO (Drioli *et al.* 2015). The reduced energy consumption results from the lower required temperature compared to traditional distillation systems. Additionally, the process generates low-grade waste and its cost-effectiveness can be further enhanced by coupling it with alternative energy sources such as solar, geothermal, and photo energy. The lower feed temperature in MD necessitates a relatively lower driving force, which does not compromise process efficiency. Presently, MBRs coupled with MD systems have been developed for treating wastewater containing organic pollutants, addressing the limitations of MBRs. These applications extend beyond the lab scale and are implemented on a commercial scale as well.

Research on the potential application of MD systems for removing organic pollutants from diverse wastewater sources has garnered significant interest. In the case of coke wastewater, a MD system effectively produced permeates within discharge limits, allowing all refractory organics to pass the hydrophobic membrane (Ren *et al.* 2018). Similarly, the municipal wastewater containing TrOCs including pharmaceuticals, steroid hormones, industrial chemicals, and pesticides, underwent MD treatment. In an experiment, the MD system successfully removed all TrOCs with pH >9, while those with pH < 9 required coupling with a MBR for complete removal (Wijekoon *et al.* 2014). This underscores the significant impact of pH and coupling on the MD system's efficiency. Notably, recent applications of coupling the MD system with other technologies are shown in Table 5.

Persistent phenolic compounds such as nitrophenol, chlorophenol, and bisphenol pose environmental hazards with prolonged toxic effects on humans and animals. An effective method for their removal is the direct contact MD process, showcasing a removal efficiency exceeding 80% (Ramos *et al.* 2021). Additionally, the separation of oil from water, particularly from petrochemical and oil and gas industries, is achieved through various methods such as dissolved air flotation, gravity and skimming, coagulation and flocculation, and hydrocyclone techniques. However, membrane-based methods stand out for stable emulsified oily wastewater due to their advantages, such as high oil removal efficiency, low operation cost, high-quality effluents, and scalability. Implementation of the membrane treatment process requires a pre-treatment process to remove or degrade organics (Han *et al.* 2017). A hybrid system, coupling MD with a two-stage pre-treatment process (oil/water separation and photocatalytic organic degradation), was developed for petrochemical wastewater treatment

Table 5 | Problems and preventions of various membrane technology

Membrane technology	Problem	Prevention	References
RO	Precipitation of iron	Backwashing cleaning process with citric acid (0.01%) as a cleaning reagent	Melliti *et al.* (2019)
Nanofiltration	Acid mine drainage due to oxidation of sulfide minerals	Chemical cleaning with 0.20% w/w hydrochloric acid (HCl)	Aguiar *et al.* (2018)
MD	Membrane scaling by inorganic crystals and membrane fouling by organic matter in feed solutions	Development of robust and super hydrophobic membrane via electro-spinning followed by electrospray to enhance membrane anti-wetting properties	Liao *et al.* (2020)
MBRs	Biofilm formation (bio fouling) induced via cell-to-cell communication (quorum sensing)	Bacterial quorum quenching along with physically (permeate) and chemically (chlorine) enhanced backwashing	Weerasekara *et al.* (2016)
Ultrafiltration	Membrane fouling caused by effluent organic matter	Ultraviolet-based oxidation pre-treatments (ultraviolet/persulfate (UV/PS) and ultraviolet/hydrogen peroxide (UV/H_2O_2))	Qu *et al.* (2021)

Table 6 | Applications of coupling the membrane distillation (MD) system with other technologies

System integrated with	Pollutants	Parameters	Results	References
Photocatalysis	4-chlorophenol (4-CP) and Ag^+ ion	Usage of BiOBr films	Degradation of 4-CP and 95% Ag^+ ion removal	Zou *et al.* (2020)
Homogeneous catalytic ozonation	TOC and salt	Temperature (327 K)	TOC (98.6%) and salt (100%)	Zhang *et al.* (2016)
Anaerobic MBR	Bulk organic matter and phosphate	Temperature (318 K)	100% removal efficiency compared to 76% by conventional MD	Song *et al.* (2018)
FO	TrOCs	Temperature (313 K)	Greater than 99.5% removal efficiency	Xie *et al.* (2013)
Electrochemical oxidation	VOCs	Temperature (343 K)	Decompose organics that MD alone could not and remove excess inorganic ions	Shin *et al.* (2020)
Osmotic MBR	TrOCs	Temperature (298 K)	Greater than 90% removal efficiency	Luo *et al.* (2017)
Anaerobic osmotic MBR	Pharmaceutically active compounds	Temperature (318 K)	The removal efficiency of 97.2% for dissolved organics	Arcanjo *et al.* (2021)
FO and electrocoagulation	Organic carbon from high-salinity brines	Temperature (333 K)	TOC (78%) and total suspended solids (96%)	Sardari *et al.* (2019)

(Table 6). Utilizing TiO_2 P25 as the photocatalyst for organic compound decomposition and microorganism inactivation, the two-stage pre-treatment process achieved a remarkable 99.5% organic degradation. In the first cycle, the system exhibited a 92% oil rejection, aiming to prevent MD fouling and reduce the production of volatile organics challenging to remove with traditional methods (Li *et al.* 2019). Integrating photothermal active nanoparticles for localized water heating can further reduce the overall system cost (Said *et al.* 2020).

2.6. Pervaporation

Pervaporation (PV), a membrane separation technique combining permeation and evaporation, selectively removes volatile compounds through a permeable membrane, diffusing them to the opposite sides (Figure S6). The receiving side, equipped with a vacuum or the purge gas, facilitates the separate collection of removed compounds. Depending on the membrane's selectivity, PV finds applications in dehydrating organic solutions or removing organic contaminants from wastewater. Its extensive application spans diverse fields, including petrochemicals, food, biotechnology, pharmaceuticals, desalination, and various industrial sectors, offering higher separation capabilities and potential energy savings of 40–60% (Sekulić *et al.* 2005). The efficiency of the PV process hinges on the selectivity of the membrane. Recent advancements have led to investigating and developing various membrane types, including polymers, ceramics, and composites (De Bruijn *et al.* 2003). Polymer membranes, widely accepted, possess unique functionalities such as energy conversion, substance recognition and separation, superior permeation and flux, and efficient substance transfer.

Various polymeric membranes, including polydimethylsiloxane (PDMS), have been developed for PV separation in organic wastewater treatment. In a PV process targeting cyclohexane-containing wastewater, a PDMS membrane demonstrated a remarkable separation factor of 2,500 under operating conditions of 300 K temperature and a vacuum pressure of 10 mmHg (Rezakazemi *et al.* 2018). PV membrane separation is a widely used for ethanol/water separation. The integration of a PDMS membrane with the fermentation process holds promise for efficient bioethanol production. Testing the PDMS polymer membrane involved removing ethanol from water through integrated PV with batch ethanol fermentation. This system can be coupled with mechanical vapor compression for enhanced performance (Fan *et al.* 2017). With a separation factor ranging from 8 to 11.6, the integrated process demonstrated a high ethanol production rate on the permeate side of the membrane. This environmentally friendly and energy-saving approach holds promising prospects for long-term operation (Fu *et al.* 2016).

Phenolic compound mass transfer is reduced in membranes such as PDMS and urethane during PV separation of phenol-containing mixtures. To address this, alternative membranes have been devised to enhance separation efficiency and permeability. Cao *et al.* explored phenolic compound separation in an aqueous solution using a poly(ether-b-amide) (PEBA) PV membrane at 30–70 operating conditions. Both permeation flux and enrichment factor rose with temperature, while the enrichment factor declined with higher feed concentration (Cao *et al.* 2021). A PEBA membrane and a PVDF membrane were developed to recover high-purity aniline from an aqueous solution. The impact of feed concentration and temperature on separation performance was examined. At 80°C and a 3 wt.% feed concentration, the membrane exhibited outstanding performance, achieving 65.1% purity of aniline and a separation factor of 35. Scaling up this process should be considered, as it proves to be an effective method for separating high-boiling-point organic compounds from aqueous solutions (Wang *et al.* 2021a). When using the PDMS membrane alone, the removal efficiency of acetonitrile from the aqueous solution was only 47%. High salt in water positively influenced PV performance and the separation factor (Wang *et al.* 2018).

The PV process efficiently separates compounds forming azeotropes. Introduced in 1976 (Aptel *et al.* 1976), gained wide acceptance for azeotropic mixture separation research. A hybrid PV-distillation system was designed to reduce energy consumption in solvent recovery towers for ester/alcohol/water mixture. Compared to the traditional distillation system, the hybrid system cut annual cost by 36.03% (Li *et al.* 2022), proving more economical. PV-extractive distillation outperforms conventional methods for azeotropic mixtures. For challenging cyclohexane and isopropanol (IPA) azeotropes, combining distillation with PV lowers annual costs by 13.98% and CO2 emissions by 15.09% (Zhang *et al.* 2021). Toth *et al.* explored a hybrid distillation-hydrophilic PV system for ethanol separation from pharmaceutical wastewater, achieving up to 99.5 wt.% purity (Toth *et al.* 2018). PV also excels in integration with photocatalysis; a PVDF membrane with photocatalytic TiO_2 rejected total dissolved solids (TDSs) at 2.345 mg/L and showed 98.02% color removal (Elma *et al.* 2022).

Various pathways, including membrane surface modification, enhance membrane separation. Introducing SiO_2 particles enhances membrane surface properties, expanding membrane technology applications in organic wastewater treatment. In a composite of PDMS/PVDF with SiO_2 particles, the separation factor was 2.5 times higher than a PDMS/PVDF membrane (Li *et al.* 2018a). Similarly, layering polyethyleneimine membranes with GO improved organic carbon rejection to 90.8%, enhancing flux rates. This suggests the promising use of GO as an incorporation material in PV membranes (Wang *et al.* 2021b).

2.7. Forward osmosis

FO effectively removes organic pollutants, even as small as 200 Da, such as pesticides, endocrine disruptors, and pharmaceutical molecules (Figure S7). These challenging separations for traditional membrane technologies are overcome by FO. Here, organic compounds move from the feed solution to the draw solution through a semi-permeable membrane, driven solely by the osmotic pressure gradient without external pressure (Madsen *et al.* 2015). FO exploits the natural tendency of water molecules to flow from low to high solute concentration across a semi-permeable membrane (Cath *et al.* 2006). The process involves a semi-permeable membrane separating a diluted feed solution from a concentrated draw solution, allowing water flow while blocking solutes. The osmotic pressure gradient propels water from the feed to the draw solution, concentrating the feed and diluting the draw solution (Cath *et al.* 2006). The diluted draw solution produces pure water, while the concentrated feed solution undergoes contaminant removal. FO operates with either natural osmotic pressure or external pressure, the latter leveraging the solute concentration difference. External pressure on the draw solution enhances the concentration gradient, increasing water flux (Cath *et al.* 2006).

An experiment reported, FO effectively concentrated organic matter in sewage, so the COD in the concentrate increased by 300% (Zhang *et al.* 2014). Another study found FO to be more effective than RO in removing organic compounds such as phenol, aniline, and nitrobenzene from wastewater (Sauchelli *et al.* 2018). In RO, rejection of charged TrOCs involves electrostatic interaction and size exclusion, with increased molecular weight enhancing TrOC rejection (Alturki *et al.* 2013).

A forward osmosis membrane bioreactor (FOMBR) effectively removed Ibuprofen (IBU) as a TrOC, achieving average removal efficiencies exceeding 96.32% (Yao *et al.* 2021). Processes enhancing water production include pressure-assisted forward osmosis, which increased water production by 9 and 29% under applied pressures of 2 and 4 bar, respectively (Jamil *et al.* 2016). Furthermore, forward osmosis with electrochemical oxidation (FOwEO) was developed to reject trace antibiotics from the wastewater. In a nearly 3-h experiment, FOwEO exhibited over 98% rejection of antibiotics (Liu *et al.* 2015).

Commonly used membranes for FO include CA, polysulfone, PES, polysulfone, polybenzimidazole, and PA (Alsvik & Hägg 2013). A comparison between commercial CTA and TFC PA membranes was conducted to assess the rejection of pharmaceutical compounds (carbamazepine, diclofenac, IBU, and naproxen). TFC exhibited superior overall performance, featuring high water flux, excellent pH stability, and effective rejection of all targeted compounds compared to CTA (Jin *et al.* 2012). Whereas, TFC membranes were superior to CTA in various aspects such as water permeability, selectivity, flux, and swelling (Sauchelli *et al.* 2018). TFC outperformed CTA in water permeability, selectivity, flux, and chemical cleaning efficiency (Coday *et al.* 2015). Evaluation of CTA and TFC membranes for fouling and performance, considering water flux, reverse salt flux, and specific reverse salt flux, revealed steady performance for CTA after 1 week, while TFC showed variations (Bell *et al.* 2017).

Feed solution pH and draw solute significantly impact the filtration performance and rejection of the FO process. A study of model compounds such as cyclohexane carboxylic acid (CHA), 1-adamantane acetic acid (AAA), and a refined Merichem mixture of naphthenic acid (NA) revealed pH-dependent rejection for CHA and AAA (pH 3–9), while NAs exhibited a consistent 95% rejection unaffected by pH (Zhu *et al.* 2018).

The FO system offers major advantages, including high water permeability, solute rejection, water recovery rates, low fouling, and energy consumption, alleviating water supply stresses and promoting power generation (Ge *et al.* 2013). This system is effective in concentrating radioactive liquid waste in hospitals. FO outperforms ultrafiltration and RO in rejecting both natural and radioactive iodine, with a 99% rejection rate for oil from wastewater (Yadav *et al.* 2020).

A significant drawback of the FO process is the inefficient removal of small neutral organic compounds. This challenge can be addressed by employing biomimetic membranes, known for selectively rejecting only three TrOCs (Madsen *et al.* 2015). Another drawback is membrane fouling, but combining MD with FO membranes can mitigate the deposition of organic and particulate matter on the membrane surface, reducing fouling (Xie *et al.* 2013). Currently, all FO processes have been conducted on a benchmark scale with limited operation time. Thus, future studies ought to explore the technology in large-scale filtration processes (Blandin *et al.* 2020).

2.8. Liquid membrane

Liquid membrane (LM) technology utilizes liquid surfactant membranes in a drop column, offering high effectiveness in hydrocarbon separation. In this process, droplets of a hydrocarbon-containing feed solution are injected into an aqueous solution containing surfactants (Li 1968, 1978). LM transport combines liquid–liquid extraction and membrane separation into a single continuous device. It employs an extracting reagent solution immiscible with water, flowing between two aqueous solutions or gases known as the source (or feed) phase and the receiving (or strip) phase. Typically, the source and receiving phases are aqueous, while the membrane is organic, although the opposite configuration is possible. The membrane can be made of either a polymeric or inorganic microporous support, serving as a bearer (in supported liquid membrane (SLM)) or a barrier (in many bulk liquid membrane (BLM) technologies), or omitted entirely (in emulsion liquid membrane (ELM) and layered BLM).

Solute transport in the LM primarily relies on the solution-diffusion mechanism, where solute species dissolve in the LM and diffuse across it due to a concentration gradient. The efficiency and selectivity of transport can be enhanced by introducing a mobile complexation agent (carrier) into the LM, which reacts with the desired solute to form a complex. This process, known as facilitated or carrier-mediated LM separation, is often combined with counter- or cotransport of different ions through LM to provide the energy for the uphill transport of the solute (Noble & Way 1987).

A thin gas or liquid film forms a barrier in the LM, separating two miscible liquids. Over the past two decades, LM technology has expanded its applications in chemical and pharmaceutical technology, biotechnology, food processing, and environmental engineering (San Román *et al.* 2010). Additionally, LM-based extractions can determine the concentration of freely dissolved pollutants on a time-weighted average basis, making them suitable for exposure risk assessment of metal ions in both environmental and biological samples (Chimuka *et al.* 2004). Moreover, the non-equilibrium mass transfer in the LM process offers advantages such as a greater driving force for mass transfer and minimal extractant quantity required (Li & Chen 2005). LM systems can also be automated and integrated with other separation techniques.

Phenols are commonly found in industrial wastewater and surface waters, posing environmental and health risks. An experiment using a SLM with tributyl phosphate (TBP) and sesame oil as the LM effectively extracted phenol under optimal conditions: 200 mg/L phenol concentration, 40% carrier concentration (%TBP), feed phase pH of 2, and stripping phase concentration of 1.1 M (Kazemi *et al.* 2014). Additionally, hydrophobic polypropylene membrane contactors, using Cyanex 923 as an extractant, achieved rapid phenol recovery, with a concentration ratio of approximately 39-fold and a 98% recovery rate (Reis *et al.* 2007). In the treatment of wastewater containing 1,050 mg/L nitrophenols, a LM process was employed, utilizing various parameters such as 2% surfactant concentration in the oil phase, 2% NaOH concentration in the internal water phase, a 2:1 ratio of oil phase to internal water phase, pH 2 in the external water phase, and a 3:1 ratio of external water phase to emulsion phase, resulting in a removal rate exceeding 99.99% for nitrophenols in wastewater (Luan & Plaisier 2004).

Efficient extraction of Palladium (Pd) from electroplating wastewater was achieved using a novel LM formulation with phosphonic acid groups as a carrier through the ELM process. Optimal conditions included 0.2 M Cyanex 302, 1.0 M thiourea in a 1.0 M H_2SO_4 stripping agent, 1:3 treatment ratio, pH 3 in the feed phase, and a 5-min extraction time, resulting in a maximum Pd extraction efficiency of 97% and a recovery of 40% (Othman *et al.* 2011).

Furthermore, chromium was successfully extracted from a wastewater solution containing waste sodium dichromate recovered from the pharmaceutical industry using the ELM technique. The LM consisted of kerosene oil as the solvent, SPAN-80 as the surfactant, potassium hydroxide as an internal reagent, and trioctylamine as the carrier. Response surface methodology optimization yielded the following conditions for optimal chromium extraction: a feed concentration of 224.04 ppm, pH 2.76, internal reagent concentration of 0.71 N, and a surfactant concentration of 1.92% (w/w), resulting in a maximum chromium extraction of 92.50% (Othman *et al.* 2011).

Additionally, an ELM was employed to extract Red 3BS reactive dye from an aqueous solution. Tridodecylamine (TDA) served as the carrier agent, salicylic acid (SA) was used to protonate TDA, sodium chloride acted as the stripping agent, and kerosene served as the diluent. SPAN 80 was utilized as an emulsifier. Under optimal conditions including 0.1 M SA, a 5-min extraction time, 3% (w/v) SPAN 80 concentration, 0.3 M NaCl concentration, 0.1 M TDA concentration, 350 rpm agitation speed, 12,000 rpm homogenizer speed, 10 min of emulsifying time, and a 1:15 emulsion to reactive dye solution ratio, nearly 100% removal of Red 3BS dye was achieved (Othman *et al.* 2011).

3. MEMBRANE FOULING

Membrane fouling stands as a significant challenge, greatly impeding the overall performance of membrane-based processes (Table 7). The accumulation of suspended solids, microorganisms, or organic substances within the membrane pores results in decreased permeate flux and the onset of membrane fouling. This fouling can manifest in various forms: (a) biological fouling stemming from the deposition and growth of biofilms on the membrane, (b) colloidal fouling caused by the buildup of microorganisms, biological detritus, polysaccharides, lipoproteins, clay, silt, oils, iron, and manganese oxides, (c) organic fouling due to the deposition of organic compounds, or (d) inorganic fouling (scale) brought about by the deposition of inorganic salts such as $CaSO_4$, $CaCO_3$, and SiO_2 on the membrane surface. The extent of membrane fouling is influenced by various factors, including feed characteristics such as pH and ionic strength, membrane properties such as roughness and hydrophobicity, and process conditions such as cross-flow velocity, trans-membrane pressure, and temperature (Shon *et al.* 2002; Obotey Ezugbe & Rathilal 2020).

Membrane fouling leads to performance degradation, alterations in membrane selectivity, and increased membrane separation resistance. These effects, in turn, impact the separation factor for target species in the feed, ultimately resulting in unstable product quality and reduced recovery (Li & Chen 2010). Several methods can be employed to mitigate fouling in

Table 7 | Pros and cons of different membrane technologies

Method	Pros	Cons	Used to treat
MF	Effectively remove particulate matter, versatile, energy efficient, simple to operate and maintain, wide range of pore sizes	Unable to remove small particles, membrane fouling, sometimes MF can be expensive (depends upon membrane and durability), complexity in changing parameters	Suspended solid, bacteria and microorganism, oil and grease, phosphorus, dyes and colors, cellulosic and fibrous materials iron and manganese
MBR	High treatment efficiency, reduced footprint, flexibility in design, enhanced nutrient removal, reduced sludge production, consistent treatment performances	High capital and operation costs, membrane fouling, energy intensive, complex operation and maintenance, chemical dependency, sensitive to shock loads	Organic compounds, biochemical oxygen demands, total suspended solid, nutrients pathogens, oil and grease, heavy metals, pharmaceutical and personal care products, dyes and colorants, and industrial effluents
RO	Highly effective filtration, versatility, compact design, selective removal, energy efficiency, reduced environmental impact	Low permeation flux, membrane fouling, inadequate selectivity, high capital and operation costs, waste generation, vulnerability to scaling	Salt and minerals, heavy metals, nitrates and nitrates, organic compounds, dissolved gases, microorganisms, PPCPs, dyes and colorants, radioactive substances, TDSs
Nanofiltration	Selective filtration, high flux rates, versatility, low energy consumption, cost-effective for certain applications	Limited salt rejection, membrane fouling, pressure sensitivity, variable membrane characteristics, complexity of operation	Hardness, dissolved salts, nitrates and nitrites, organic compounds, colorants and dyes, boron, pharmaceutical and personal care products, heavy metals, bacteria and microbes, TDSs
MD	Low operating temperature, suitable for brine concentration, versatility, potential for renewable energy integration, compact system design, reduced scaling issues	Energy intensive, membrane fouling, capital costs, complexity, limited scalability, product purity	Salt and minerals, volatile organic compounds, dissolved gases, pharmaceutical and personal care products, oil and grease, heavy metals, organic compound, colorants and dyes, nutrients, radioactive substances
PV	Energy efficiency, selective separation, operational flexibility, reduced environmental impact, no azeotropic limitation, continuous operation	Membrane degradation, membrane fouling, high capital costs, limited applicability, sensitive to feed composition, limited scalability	Organic compounds, azeotropic mixture, alcohol and esters, pharmaceutical and personal care products, volatile inorganic compounds, oil and grease, flavor and fragrant compounds, volatile acids and bases, and selective compounds removals
FO	Low energy consumption, suitable for high-salinity feed solutions, reduced fouling, potential for use in FO-driven processes, environmental sustainability, selective permeation	Draw solution challenges, limited desalination performance, membrane degradation, scaling issues, limited commercialization, complexity in system design	Salinity and TDSs, heavy metals, nutrients, dyes and colorants, organic compounds, radioactive ions, oil and grease, pathogens and microbes
LM	Selective extraction, versatility, potential for high efficiency, reduced scaling issues, operational flexibility	Membrane stability, limited selectivity, complexity in design, potential for emulsion issues, energy intensity, limited commercialization	Metal recovery, organic compound removal, acid and base recovery, color removal, oil and grease separation, pharmaceutical wastewater treatment, radioactive waste treatment, selective ion removal

membranes, including pre-filters, surface shearing, chemical agents, and adjustments to operational conditions. Additionally, techniques such as ultrasound, backflushing, membrane oscillation, chemical cleaning, pore structure optimization, and membrane surface modification offer effective options for fouling mitigation (Jepsen *et al.* 2018; Ullah *et al.* 2021). A novel electro-assisted membrane coupling technology has contributed to addressing this problem by repelling foulants such as charged natural organic matter, colloids, and bacteria from membrane surfaces in the presence of an electric field (Li *et al.* 2018b).

4. FUTURE CONSIDERATION AND CONCLUSION

As the global water crisis escalates, the search for effective and sustainable water purification technologies becomes increasingly crucial. Membrane technology, known for its efficiency and energy-conscious design, stands as a forefront solution to this challenge. Despite significant progress in water and wastewater treatment through material and module advancements, certain critical areas demand continuous attention. Fouling control and the pursuit of energy-efficient devices represent two key focal points for future exploration.

The persistent challenge of foulant accumulation on membranes requires innovative solutions. Research should focus on developing fouling-resistant membranes and exploring cost-effective pre-treatment techniques. A collaborative approach could yield breakthroughs in overcoming fouling, thereby enhancing the long-term efficiency of membrane systems. Energy efficiency remains an essential goal. Although the energy consumption of membrane processes has been significantly reduced, ongoing research is crucial to discovering novel ways to conserve energy in membrane-based water purification. Exploring hybrid techniques, such as the synergistic combination of forward-RO, holds immense promise. This hybrid approach, exemplified by its ability to eliminate high concentrations of phosphorus, ammonium, and salt from wastewater, signifies a leap toward resource-efficient water treatment.

As the research community refines these solutions, anchoring advancements in future economic viability and sustainability is essential. The application of cutting-edge technologies must align with practical constraints, emphasizing cost-effectiveness and environmental stewardship. Interdisciplinary collaboration and partnerships between researchers, engineers, policymakers, and industry players will play a crucial role in shaping the trajectory of water purification innovation. In conclusion, the journey toward enhanced water purification is not merely a scientific pursuit but a collective commitment to securing a sustainable water future. Through ongoing research, innovation, and collaborative efforts, the promise of accessible, clean water for all remains within our reach.

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AUTHOR CONTRIBUTIONS

S. R. K. conceptualized, drafted, edited, and commented on the manuscript. S. A. and R. S. drafted, edited, and commented on the manuscript. S. B., G. K., P. G., and N. T. edited and commented on the manuscript. A. T. drafted, structured, edited, and commented on the manuscript. G. J. structured and edited. All authors have read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare there is no conflict.

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