

# FUTURISTIC TRENDS IN ADVANCED INDUSTRIAL MEMBRANE PROCESSING TECHNOLOGIES

## Abstract

This chapter delves into the pervasive utilization of membranes across various industries, spanning metal, food, biotechnology, textile, pharmaceuticals, and more. Membranes have emerged as a versatile solution, addressing pressing global challenges like energy scarcity, water management, environmental protection, and the shift towards renewable energy sources. With the looming depletion of fossil fuels, membranes play a pivotal role in transitioning to low-emission energy alternatives such as hydrogen and biofuels, while also aiding in reducing CO<sub>2</sub> emissions from conventional power plants. The chapter explores the multifaceted applications of membranes, including their use in energy conversion, environmental protection, industrial processing, and wastewater treatment. From nano-composite gas separation membranes to membrane bioreactors for wastewater treatment, it highlights how membranes enhance efficiency and sustainability in diverse processes like edible oil recovery, solvent dewaxing, and aromatic recovery from wastewaters. Conclusively, the chapter emphasizes the monumental strides in membrane science and technology, envisioning a future where integrated membrane processes revolutionize industrial cycles, elevating energy efficiency, product quality, and environmental impact. It provides insights into the potential evolution of membrane engineering and its profound impact on long-term industrial growth and sustainability.

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## I. INTRODUCTION

The Latin word “membrane,” which means “skin,” is where the word “membrane” originates (Jones, 1987). Due to its semi-permeable qualities, a thin, flexible sheet or film that serves as a selective boundary between two phases is now referred to as a membrane. A membrane can be either solid or liquid physically. It is a highly selective separation agent based on differences in diffusivity coefficient, electric current, or solubility. The membrane is now an essential component of our daily lives. All living cells, including us, are encased in a membrane. Membrane cells in living things are highly selective and only transfer certain species.

The use of membranes is widespread in many industries today, including the metal, food, and biotechnology sectors (for separation, purification, sterilisation, and by-product recovery), the leather and textile sectors (for sensible heat recovery, pollution control, and chemicals recovery), and the metal, food, and biotechnology sectors (for metal recovery, pollution control, and air enrichment for combustion) (Wenten, 2005). Pulp and paper industries (replacing the evaporation process, pollution control, fibre and chemicals recovery) and chemical process industries also use membrane technology (organic separation, gas separation, recovery, and recycling chemicals). Health, pharmaceutical, and medical businesses (artificial organs, control release (pharmaceuticals), blood fractionation, sterilisation, water purification), as well as waste management, are all included in the medical sector (separation of salt or other minerals and deionisation).

## II. MEMBRANES AND MEMBRANE PROCESSES

In a perm selective barrier or an interphase between two phases, the membrane is at the centre of any membrane process. The capacity of the membrane to carry one component from the feed mixture more readily than any other component or components allows for separation. Two factors—selectivity and flow through the membrane—determine the effectiveness or performance of a specific membrane. The latter is frequently referred to as the flux or permeation rate, defined as the volume that permeates the membrane per unit area per unit time. The selectivity of a membrane is determined by the molecular size and shape of the molecules passing through the membrane, as well as their affinity to the membrane material and the distribution of polar or non-polar groups within the membrane material. In perm selective barriers, some components of the feed mixture will pass through the membrane more easily than others, depending on the selectivity of the membrane and the affinity of the components for the membrane material. The flux of a membrane is determined by many factors, including the temperature, pressure and pH of the feed, the membrane material and thickness, and the flow rate of the feed. The permeation rate of a membrane can be improved by increasing the temperature, pressure and pH, while reducing the thickness and increasing the flow rate of the feed. The flux can also be improved by using a membrane material with a higher permeability.

Transport across a membrane can be active or passive, driven by various factors (such as pressure, concentration, or electrical difference), and neutral or charged. A membrane can be natural or synthetic, thick or thin, and its structure can be homogeneous or heterogeneous. Membranes can therefore be categorised in a variety of ways. The first division is based on kind, such as biological or artificial membranes. This contrast is as distinct as it can be. Organic (polymeric or liquid) and inorganic (such as ceramic or metal) membranes are two

categories under which synthetic membranes fall. Another way to categorise membranes is based on their morphology or structure. There are two types of membrane structures for solid synthetic membranes: symmetric and asymmetric (anisotropic). The symmetry of a membrane is determined by the arrangement of its components. Homogeneous (isotropic) membranes are made of one material, while heterogeneous (anisotropic) membranes are composed of two or more materials.

The type of transport across a membrane can also be classified. The types of transport across a membrane include passive transport, active transport, osmosis, facilitated diffusion, and endocytosis. Passive transport is the movement of substances through the membrane without the use of cellular energy. Passive transport does not require energy and is driven by a concentration or pressure gradient. Active transport is the movement of substances against their concentration gradient with the use of cellular energy. Finally, the charge of the substance being transported across the membrane can be considered. Osmosis is the movement of water molecules through a semi-permeable membrane. Facilitated diffusion Active transport does require energy and is driven by ion pumps or other mechanisms. is the movement of substances down their concentration gradient with the use of a membrane protein. Endocytosis is the process of a cell taking in large molecules or particles by engulfing them with its cell membrane. Neutral molecules and ions can be transported across the membrane, as well as charged particles.

Because the membrane and the permeating components have different physical and/or chemical properties, the membrane can carry some components more quickly than others. A driving force acting on the feed's components causes them to move across the membrane. Pressure, concentration, electric potential, or temperature gradient can all act as driving forces. The membrane itself is the primary determinant of selectivity and flow, in addition to the pushing force. The kind of application, which can range from the separation of microscopic particles to the separation of molecules of the same size or shape, is determined by the membrane's nature. For instance, a membrane with defined pore size can selectively allow components of a certain size to pass through while rejecting those that are too large or small. Similarly, a membrane with a hydrophilic or hydrophobic surface can be used to selectively allow polar or non-polar molecules to pass through.

Various pressure-driven membrane techniques can concentrate or purify a diluted solution, regardless of whether it is aqueous or non-aqueous. The distinction between these processes lies in the continuous phase of the solvent and the relatively low concentration of solutes. Membrane structure and solute particle size play crucial roles in identifying different procedures, such as reverse osmosis, microfiltration, ultrafiltration, and nanofiltration. A comparison of various procedures can be found in the following table (Table 1).

**Table 1: Comparison of pressure-driven membrane processes**

| Parameters                 | Microfiltration         | Ultra filtration             | Nanofiltration/Reverse Osmosis   |
|----------------------------|-------------------------|------------------------------|--|
| Separation characteristics | Separation of particles | Separation of macromolecules | Separation of low MW solutes (salts, glucose, lactose, micro-pollutants) |

|   |                                       |  |  |
|---|---------------------------------------|--|--|
| Osmotic pressure                        | Negligible                            | Negligible   | high ~ 1 - 25 bar  |
| Applied pressure                        | low < 2 bar                           | low ~ 1- 10 bar  | high ~ 10 - 60 bar   |
| Structure                               | Symmetric<br>/Asymmetric              | Asymmetric   | Asymmetric   |
| Thickness of actual<br>separating layer | Symmetric ~ 10 -<br>150 $\mu\text{m}$ | ~ 0.1 - 1.0 $\mu\text{m}$  | ~ 0.1 - 1.0 $\mu\text{m}$  |
| Pore size                               | 0.05 - 10 $\mu\text{m}$               | 1 - 100 nm   | < 2 nm   |
| MWCO                                    | < 1,00,000 Da                         | 10,000 to 1,00,000<br>Da   | 1,000 to 1,00,000 Da<br>(NF)   |
|   |                                       |  | 100 to 1,000 Da (RO)   |
| Basis of separation                     | Particle size                         | Particle size  | Differences in<br>solubility and<br>diffusivity  |
| Application                             | Clarification, water<br>treatment     | Whey and protein<br>processing,<br>clarification, dairy,<br>textile,<br>pharmaceutical | Desalination of<br>seawater, the<br>concentration of fruit<br>juices and milk,<br>desolventization |

Compiled from Mulder, 1998

- 1. Micro filtration:** Macromolecules, colloids, and suspended particles can all be concentrated, purified, or separated from the solution using the pressure-driven separation technique known as microfiltration (MF). For purposes including wine, juice, and beer clarity, wastewater treatment, and plasma extraction from the blood for therapeutic and commercial uses, MF processing is extensively employed in the food industry. Examples of MF in biotechnology include cell recycling and harvesting, separating recombinant proteins from cell detritus, and stream purification. In terms of process modification, MF has also been used for particle size reduction, clarification, virus removal, and other applications.

MF utilizes a membrane, typically made of synthetic polymers such as polysulfone, polyvinylidene fluoride, and polyethersulfone. The membrane is semi-permeable and is typically rated by the smallest particle size it can retain. The feed solution is pumped through the membrane and the particles are filtered out, leaving a clarified solution on the other side. Depending on the application, the membrane can be used in crossflow or dead-end mode, and the feed solution can be pressurized or vacuum driven. The advantage of MF lies in its ability to target specific particle sizes and achieve high purity, while not being affected by the pH or ionic strength of the solution.

- 2. Ultra filtration:** Ultrafiltration membranes are predominantly utilized for the purpose of fractionation or segregation of high-molecular-weight solutes from low-molecular-weight solutes. A notable distinction from reverse osmosis membrane systems lies in the considerably reduced hydraulic pressures required to facilitate the process, owing to the larger pore diameters of ultrafiltration membranes. As a consequence of this characteristic, such membranes find efficacy in the filtration of substantial solutes, including proteins, viruses, and bacteria, from various liquid mediums. Moreover, they

prove effective in the elimination of impurities and pollutants from water, wastewater, and other liquid streams.

The applications of ultrafiltration membranes encompass a wide array of industries and processes. Notably, they are instrumental in the purification of food and beverages, the production of enzymes, and the removal of heavy metals from industrial wastewater. Through these diverse applications, ultrafiltration membranes contribute significantly to the enhancement of product quality, environmental remediation, and the overall sustainable development of various sectors.

- 3. Nano filtration:** A pressure-driven membrane process is a nanofiltration. Nanofiltration employs lower pressures and filters with more significant pore sizes than reverse osmosis. It is a pressure-driven membrane method commonly used to remove solutes from aqueous streams with molecular weights between 200 and 1000  $\text{g}\cdot\text{mol}^{-1}$ . Applying organic solvents to nanofiltration techniques is a breakthrough known as organic solvent nanofiltration (OSN). OSN is a topic of intense research at the moment (Lavania et al., 2021). Nanofiltration has great promise for separating molecules found in organic solvents in various industries, including precision chemical and pharmaceutical production. OSN is a relatively new technology and has the potential to be a cost-effective and energy-efficient alternative to traditional organic solvent separation and purification techniques.
- 4. Reverse osmosis:** In Reverse Osmosis (RO) membrane processes, the permeation process solely permits the passage of the solvent, precluding any migration of solute species, whether organic or inorganic, into the permeate. This separation phenomenon is governed by intricate interactions between the solute species and the membrane, wherein factors such as molecular shape, size, and ionic charge play crucial roles. RO, being an environmentally sustainable approach, finds extensive application in diverse fields, encompassing water reuse, groundwater purification, and the treatment of boiler feed water to recover wastewater. Despite its wide-ranging utility, the efficacy of this technology is impeded by the considerable osmotic pressures encountered in treating seawater or effluents bearing high total dissolved solids. Consequently, it is not deemed suitable for desalination of seawater or the recovery of wastewater in such scenarios.
- 5. Gas separation:** Gas separation relies on passing a gas mixture at high pressure across a selective membrane that allows only one component of the feed mixture to pass through, resulting in an enriched permeate containing this specific species. Currently, gas separation membranes find significant application in various fields:
  - Nitrogen synthesis from air: Gas separation membranes are utilized to extract nitrogen from the air, producing a purified nitrogen stream.
  - Carbon dioxide separation from methane in natural gas operations: Gas separation membranes help separate carbon dioxide from methane in natural gas processing, enabling the production of cleaner and more valuable methane gas.
  - Hydrogen separation from nitrogen, argon, and methane in ammonia plants: Gas separation membranes play a crucial role in ammonia plants by separating hydrogen from other gases like nitrogen, argon, and methane, thereby obtaining high-purity hydrogen for further use.

These diverse applications demonstrate the importance of gas separation membranes in facilitating the extraction and purification of specific gases, contributing to various industrial processes.

Gas separation membranes are typically made from polymers, metal, or ceramic materials, and can be either inorganic or organic. Polymeric membranes are the most common type, and can be used for a wide range of gas separations. These membranes have the advantage of being able to be tailored to specific applications and are typically less expensive than other types of membranes. Metal membranes are often used for high-pressure separations, and ceramic membranes are used for separations of oxygen and nitrogen.

Gas separation membranes are typically characterized by their permeability, selectivity, and flux. Permeability is a measure of the rate of gas transport through a membrane, selectivity is a measure of the separation of the components of a mixture, and flux is a measure of the total amount of gas that can pass through the membrane. The effectiveness of a gas separation membrane is determined by the combination of these three parameters.

- 6. Pervaporation:** A liquid combination meets one side of a membrane during pervaporation, and the permeate is evacuated from the opposite side of the membrane as a vapour. The low vapour pressure on the permeate side of the membrane created by chilling and condensing the permeate vapour is what drives the process. The appeal of pervaporation lies in the fact that the extent of separation is inversely proportional to the rate at which the components of the liquid mixture permeate through the selective membrane. This unique characteristic makes pervaporation an attractive option for separating closely boiling mixtures or azeotropes, which can be difficult to separate using traditional methods like distillation or other techniques. Pervaporation offers a viable solution to tackle these challenging separation scenarios, making it a valuable and versatile separation process in various industries. Additionally, methods for separating organic mixtures and removing dissolved organics from water using pervaporation are being developed.

### III. EMERGING MEMBRANE PROCESSING TECHNIQUES

Membrane technology has emerged as an effective and adaptable method in our daily lives. The globe faces more complex issues than ever in the twenty-first century, including managing rising energy demands, ensuring appropriate water supplies in both rich and developing nations, reducing the effects of global warming, and safeguarding our environment. Membranes will increasingly be required to address these problems in various applications.

- 1. Membranes for energy conversion:** Globally, the energy policy is evolving. There are several causes for this, including In fewer than 50 years, fossil fuels will become scarce; more than 64% of the world's existing petroleum reserves are in the Middle East, while less than 14% are present in Europe, the United States, and the former USSR region combined. Security concerns arise from energy independence. As a result, various low-emission renewable energy solutions are being deployed, emphasising the usage of

hydrogen and biofuels to power our future. In a moment of transition when coal and petroleum are still the two most common fuel sources, conventional power plants and refineries are encouraged to modernise to cut their CO<sub>2</sub> emissions. Membranes have a significant chance to play a significant role in all of these new technologies and transitional phases.

- **Fuel cells:** Fuel cells serve as the primary zero-emission energy converters, playing a crucial role in powering various applications such as vehicles, portable electronics, and buildings. These versatile energy devices can be fuelled with hydrogen or renewable fuels like methanol and ethanol. To enable high-temperature operation, extensive research has been conducted on proton-conducting polymer electrolyte materials. Two types of membranes can be recommended based on the water's involvement in proton conduction. Some membranes, like perfluorosulfonic membranes, require humidification to maintain their optimal conductivity, as water molecules are essential for the proton mobility process in these materials. The amount of humidification needed depends on the operating temperature and membrane characteristics, which, in turn, influences the device's size and complexity.

In contrast, certain electrolytes may not technically necessitate humidification, as their proton conduction process does not rely on water molecules. However, these systems may face challenges related to short-term stability, such as phosphoric acid leakage from the membrane during operation. Additionally, they may experience limitations in the extension of the three-phase reaction zone inside the electrodes due to the lack of a suitable ionomer, and inorganic proton conductors may exhibit decreased conductivity levels (Tchicaya-Bouckary et al., 2002).

Therefore, fuel cells offer an environmentally friendly energy conversion solution, and the choice of the appropriate membrane type and humidification strategy depends on the specific application and operating conditions. Further research and development in this field aim to address the drawbacks and improve the overall performance and stability of fuel cell systems.

- **Hydrogen separation:** The periodic table's lightest element, hydrogen, is mostly used as a chemical building component in numerous chemical processes. Nearly 96% of hydrogen produced today comes from fossil fuels, with close to 48% coming from natural gas (methane), 30% from petroleum feedstock (oil), and 18% from coal. Electrolysis currently produces only 4% of hydrogen, but this percentage will certainly rise in the future. Nearly 50% of the hydrogen produced is used to create ammonia, with refineries and methanol synthesis coming in second and third. Only a tiny portion is being used as fuel, but as we move into the hydrogen economy, this will surely expand in the near future (Gryasnov, 2000).

The primary method widely used for hydrogen production involves steam reforming of natural gas. In this process, methane and steam are combined and subjected to a catalytic reaction at high temperatures and pressures (typically 700-900°C and 30 to 40 bar). The reaction is governed by thermodynamic equilibrium, and to enhance hydrogen conversion, shift reactors (both high and low temperature) are employed. To optimize the overall conversion of the process, a preferred oxidation reactor (PreOx) and a hydrogen separator are utilized.

However, a drawback of this process is that it produces CO<sub>2</sub>, a greenhouse gas that requires proper treatment before being released into the atmosphere due to its environmental impact. To improve the total conversion of thermodynamic equilibrium-controlled reactions, a membrane reactor is an effective approach. By continuously removing one or more of the reaction products during the process, a membrane reactor significantly enhances reaction efficiency, making it particularly suitable for steam reforming reactions (Klette & Bredesen, 2005).

In steam reforming applications, metallic membranes, especially those composed of Pd and Pd/alloy supported on porous metal, offer distinct advantages. These metallic membranes, along with their porous support, exhibit excellent chemical, mechanical, and thermal stability, even at high temperatures and pressures. Compared to standalone thin films, composite membranes supported by porous metal provide both the benefits of a thin membrane layer and the necessary mechanical strength for high-pressure applications. This makes them well-suited for use in hydrogen production processes.

- **CO<sub>2</sub> capture and power generation:** Power generation accounts for approximately one-third of the principal anthropogenic CO<sub>2</sub> sources. Efforts to develop CO<sub>2</sub> reduction technology have been prompted by a growing consensus that this emission leads to a rise in global temperature, which has enormous potential consequences. This can be done by implementing numerous strategies at once, including:
  - Increasing energy effectiveness
  - Using low-carbon fuels or CO<sub>2</sub>-neutral or non-emitting methods for producing electricity and chemicals,
  - Creating technologies for the capture and storage of CO<sub>2</sub>.

Membranes might be crucial in the many CO<sub>2</sub> mitigation solutions mentioned above (Powell & Qiao, 2006). The traditional methods of separating CO<sub>2</sub> are membrane technology, cryogenic distillation, adsorption, physical and chemical absorption, and adsorption. Polymer composites incorporating polar ether oxygens (Lin & Freeman, 2005) and/or amine groups are two different methods for producing materials for membranes with preferential CO<sub>2</sub> transport. The use of polymers containing segments made of ethylene oxide is a method that various parties are researching. Recently, highly branched, cross-linked poly (ethylene oxide) with up to 30 times higher CO<sub>2</sub>/H<sub>2</sub> selectivity was found.

Additionally, it has been demonstrated that inorganic membranes can be used with CO<sub>2</sub> capture in a variety of fossil fuel-based power cycles. Studies comparing the efficiency of the power cycle reveal that membrane integration can absorb CO<sub>2</sub> with a penalty of about 5–8%. Modern membranes have already shown sufficient flow and selectivity to provide methods for CO<sub>2</sub> capture that are affordable. However, strict control of every stage in modern production procedures seems crucial for current membranes' features. Because of this, membrane module fabrication is challenging, and extensive effort is required to achieve large-scale, economically feasible production. Several businesses are currently engaged in such initiatives and performance validation under actual operating situations (Lin et al., 2006).



**2. Membranes for environmental protection:** Two significant difficulties facing humanity in the twenty-first century are water supply and environmental protection. More effective methods of treating and reusing water are required due to the growing global population and finite water resources. Additionally, the earth has become less safe for human habitation as a result of the daily release of significant volumes of wastewater, home and industrial effluents, and other gaseous and liquid pollutants into the environment. To address this, all governments must take proactive steps to reduce the amount of pollutants released into the environment, as well as to invest in research and development of new technologies for more efficient and effective water treatment.

- **Wastewater treatment:** The manufacturing and service sectors generate significant amounts of wastewater on a daily basis, spanning various industries such as automobiles, food, steel, textiles, animal handling, processing, hotels, transportation, and more. Industrial activities account for approximately a quarter of global water consumption, highlighting the considerable water usage by these sectors. To address the issue of pollution resulting from wastewater, stringent pollution control measures and legislation have become necessary, presenting a significant opportunity for the application of membrane technology.

There are two primary methods for treating wastewater, depending on whether the permeate needs to be recycled (e.g., for alkaline/acid cleaning baths, electrocoat paint, or water reuse) or disposed of (e.g., in machining processes, food wastes, or metal plating). However, even within the same industry and sometimes within the same plant, the physicochemical characteristics of wastewater can vary significantly, particularly during different seasons of the year. This variability makes wastewater treatment more complex than many other industrial membrane applications. Thorough testing is required to account for potential fluctuations in the feed-stream composition, consider pre-treatment options, address cleaning challenges, and resolve issues related to recycling or disposing of the permeate and retentate (Cheryan, 1998).

Overall, the diverse nature of industrial wastewater necessitates careful consideration and adaptability in membrane technology to effectively and sustainably manage the treatment process and mitigate the environmental impact of these wastewaters.

- **Nuclear Waste Treatment:** The nuclear industry generates a wide range of low and intermediate-level liquid radioactive wastes (LRWs) with varying volumes, radioactivity, and chemical compositions. Traditionally, LRWs have been treated using conventional methods like chemical processing, adsorption, filtration, ion exchange, and evaporation, but these techniques have limitations in terms of contaminant removal and cost-effectiveness. Membrane technology has emerged as a promising solution for treating low-level radioactive waste in nuclear power facilities.

Membrane techniques, such as reverse osmosis (RO), ultra filtration (UF), and microfiltration (MF), offer the advantage of selectively removing radioactive contaminants from the waste stream by passing only a portion of the stream across the membrane. These membrane-based processes have already been successfully employed in cleaning up boric acid solutions for recycling, mixed laboratory wastes, and radioactive laundry wastes in nuclear power plants.

A newer technique called membrane distillation (MD) has also been introduced. MD is a separation method that uses a porous, liquid-unwettablyophobic membrane. Only vapor can pass through the membrane pores due to its liophobic nature, and condensation occurs on the opposite side of the membrane in an air gap, cooling liquid, or inert carrier gas. Hydrophobic membranes made of polymers like polypropylene (PP), polytetrafluoroethylene (PTFE), or poly(vinylidene fluoride) (PVDF) are commonly used in MD for treating water solutions. The driving force behind the MD process is the gradient of the solution's component partial pressures in the gaseous phase.

Membrane technologies have proven effective in treating various types of effluents, and in the nuclear industry, they have found applications in the removal of tritium from nuclear waste (both liquid and gaseous effluents), isotope separation, treatment of gaseous radioactive wastes, and separation of noble gases (Zakrsewska-Trsnadel et al., 2001). Despite some technical and procedural challenges, membrane-based techniques offer significant potential for addressing radioactive waste treatment needs, and ongoing research continues to improve and expand their applications in the field of nuclear materials processing industries.

- **Air Pollution:** The primary sources of air pollution include industrial activities, power plants, automobile transportation, and the improper disposal of municipal and agricultural waste. The release of acid gases like sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>), volatile organic compounds (VOCs), halogen-derived hydrocarbons, and aromatic compounds contributes to the depletion of the ozone layer and exacerbates the greenhouse effect, making air pollution particularly hazardous. To address these issues, various techniques are employed for the removal of these pollutants. These strategies are categorized based on their focus levels, and hybrid processes that combine different techniques are often economically and technically beneficial.

One critical concern in atmospheric pollution is the production of large quantities of greenhouse gases, such as carbon dioxide from the burning of carbon-based fuels, and simultaneous emissions of methane and carbon dioxide from solid waste dumps. Recovering methane from such waste is advantageous because methane is a valuable energy source with a higher global warming potential than carbon dioxide.

The concept of gas separation using membranes relies on dissolution and diffusion mechanisms. Gases generally have low solubility in polymers, typically around 0.2%, as they have a weaker affinity for polymers compared to liquids. However, when the affinity of a polymer for a specific gas increases, the gas's solubility also increases. For example, carbon dioxide exhibits higher solubility in hydrophilic polymers compared to hydrophobic ones. This property forms the basis of gas separation using membranes and allows for the effective removal of specific gases from a gas mixture.

### 3. Hybrid Processing Employing Membranes for Industrial Applications

- **Nano-composite gas separation membranes:** Simple and cost-effective membrane gas separations are attractive; however, they often suffer from limited gas flux. This challenge arises because the permeability and selectivity of a material are typically inversely related. To address this limitation, researchers have recently developed polymer-inorganic nano-composite materials that aim to improve the performance of polymer membranes. Polymer-inorganic nano-composite membranes consist of two components: a polymer matrix and an inorganic substance. These two components are combined to create the nano-composite material, where the inorganic phase is dispersed at the nanoscale level within the polymer phase. This unique structural arrangement of polymer-inorganic nano-composites enhances the gas separation properties of pure polymers.

By incorporating the inorganic phase into the polymer matrix, these nano-composite membranes can achieve higher gas flux while maintaining or even improving the desired selectivity for gas separation processes. The inorganic nanofillers are typically spread in a continuous polymer matrix, and the nano-composite membrane combines polymeric and inorganic components in a single entity. The strong inherent separation performance of inorganic nanoparticles and the robustness and mechanical stability of polymers are the driving forces for the development of the nano-composite membrane. Nano-composite membranes have several novel features not found in polymeric or inorganic membranes, owing to their synergistic effects (Sadrzadeh & Mohammadi, 2019). This advancement holds great promise for improving the efficiency and effectiveness of gas separation using membrane technology.

- **Separation of Light Hydrocarbons:** Pervaporation is a separation technique that can effectively separate solutions, mixtures of substances with similar boiling points, and azeotropes, which are difficult to separate using traditional distillation or other methods. The concept of pervaporation was initially studied systematically by American Oil in the 1950s, but it remained mostly an academic curiosity until 1982 when the first commercial pervaporation plant was established by GFT (Gesellschaft für Trenntechnik GmbH) in Germany. Following this, GFT went on to build more than 50 similar plants, with the initial focus on extracting water from concentrated alcohol solutions using composite membranes made from polyvinyl alcohol, which has higher permeability to water compared to alcohol.

Commercial pervaporation is also employed to separate water from organic substances. As water and organic solvents have significantly different polarities and membrane penetration characteristics, this separation becomes relatively straightforward. An early example of an organic-organic application was announced by Separex in 1988, where they successfully separated methanol from methyl t-butyl ether/isobutene mixtures. Cellulose acetate membranes have been commonly used and performed well in such applications, offering several advantages.

In recent developments, Exxon has introduced a evaporation pilot plant using polyimide/polyurethane block copolymer membranes to separate aromatic/aliphatic mixtures. This separation process is of particular importance in refineries. Overall, evaporation has emerged as a valuable technique for separating various challenging mixtures, and ongoing research and development continue to expand its applications in different industries, providing more efficient and effective separation solutions.

- **Solvent Dewaxing:** Reverse osmosis (RO) is finding potential new applications in the chemical sector for separating organic/organic mixtures. However, such separations present challenges due to the significant osmotic pressures that need to be overcome and the requirement for membranes that are both solvent-resistant and mechanically robust while still allowing good fluxes.

In the oil industry, the removal of waxes is traditionally achieved through chilling, settling, and separating. The conventional pressure leaf filter used in refineries has encountered issues like clogging of the filter media, trapping of neutral oil in the filter earth, and difficulties in disposal. These problems have been mitigated with the introduction of the centrifugal technique, which involves a polish filtration phase to ensure low wax concentrations in the processed oils.

Membrane technology has been explored as a potential solution to address some of the challenges faced in industrial operations. Researchers have investigated using UF and MF membranes for hexane-diluted and undiluted vegetable oils, respectively. The results showed that the MEUF (micellar enhanced ultrafiltration) approach was efficient in simultaneously degumming and dewaxing hexane-diluted oils without the need for a precooling step, offering significant energy savings. On the other hand, MF membranes were highly effective for dewaxing undiluted oils, but a precooling step was required. Moreover, this method offers the advantage of a one-step pre-treatment, reducing the burden of contaminants in subsequent steps of membrane refinement.

These advancements in membrane technology showcase its potential to improve oil refining processes, enhance efficiency, and reduce energy consumption in the chemical and oil industries. Continued research and development in this area hold promise for further optimizing membrane applications and finding novel solutions for separation challenges.

- **Edible Oil Solvent Recovery:** Miscella is the solvent-oil mixture produced during solvent extraction of oils. The miscella will typically include about 25% crude oil. The miscella is desolventized, and the resulting crude oil undergoes several refinement procedures to eliminate the main impurities, such as water, FFA, partial glycerides, phosphatides, oxidation products, pigments, and trace metals like copper, sulphur, iron, and halogens. These contaminants are eliminated throughout the conventional refining at several stages, including degumming, neutralising, washing, drying, bleaching, filtration, and deodorising. The refined oil that the refinery produces is distributed and packaged.

Processing edible oils have become one of the main areas for membrane applications because there is such a huge potential for energy savings and the chance to increase oil quality. From a conceptual standpoint, membranes could be applied to practically every step of the manufacturing and purification of oil. Several researchers have attempted the membrane processing of edible oils with and without solvents using porous and nonporous denser polymeric composite membranes.

Whilst membrane technology might be used at several phases of the oil processing process; the solvent recovery step has the most significant potential for energy savings. Creating a membrane resistant to solvents and can separate hexane from the hexane-oil miscella could lead to substantial energy savings in the oil seed extraction facilities. Researchers are searching for ideal membranes that are stable to oil and organic solvents, have high oil retention, high permeate flux, and little propensity to fouling in this endeavour. According to recent studies, up to 65% of hexane (oil-depleted permeate stream) could be returned directly to the extractor, resulting in significant thermal energy savings.

- **Membrane Aromatic Recovery System:** Membrane methods have attracted attention for their potential in removing low-volatility organics from wastewater. One such application is membrane solvent extraction, which uses porous membranes to recover organics from aqueous solutions. However, porous membranes suffer from a significant drawback - their instability. If the breakthrough pressure through the membrane is not maintained adequately, the immobilized phase in the pores can experience breakthrough, leading to reduced efficiency.

To address this issue, researchers have suggested using nonporous membranes for extraction. Nonporous membranes offer a substantially higher breakthrough pressure than porous membranes, ensuring better stability. However, the trade-off is that nonporous membranes may have a slower mass transfer rate during membrane extraction. Furthermore, membrane technology has been explored for preparing extracts of bioactive spices. In one study with turmeric oil extracted from curcumin-removed-turmeric oleoresin, volatile constituents preferentially permeated through the membrane, increasing their content from 75% to 97.8%. This result matched the quality of direct steam distilled oils. In contrast, in another study with rosemary extract in the ethanol phase, the SRNF membrane exhibited increased rejection of rosmarinic acid (rejection of 99.7%) and caffeic acid (rejection of 93.9%). As a result, these compounds concentrated in the retentate fraction.

These findings demonstrate the versatility and potential of membrane technology in various applications, ranging from wastewater treatment to the preparation of valuable bioactive extracts from natural sources. Researchers continue to explore and optimize membrane methods to overcome challenges and improve their efficiency in diverse fields.

- **Membrane Bio-Reactor:** Membrane bioreactors (MBRs) offer several advantages over traditional biological processes for wastewater treatment. MBR combines two essential processes, biological degradation and membrane separation, to create an efficient and effective treatment system. Activated sludge, a common biological process, is often integrated with membrane technology in MBRs for wastewater treatment. These systems are widely used to treat wastewater from various industries, including food and beverage processing, metal fabrication, automotive, cosmetics, and landfill leachate.

In a bioreactor, a biologically active environment is created to support the growth of bacteria and protozoa (referred to as biomass) that consume and break down the constituents of raw wastewater. The type of bioreactor used can vary based on the need for oxygen and nitrates, and they can be aerobic (for organic matter removal and ammonia oxidation to nitrate), anoxic (for nitrogen removal from nitrates to nitrogen gas), or anaerobic (for organic matter removal).

Membranes play a crucial role in the MBR process as a solid-liquid separation mechanism. They retain the biomass inside the bioreactor while releasing the treated effluent to the environment. Membranes replace the clarifiers used in the conventional activated sludge (CAS) process. MBR applications can use microfiltration (MF) and ultrafiltration (UF) membranes. UF membranes are often preferred due to their superior separation properties, allowing them to remove colloids and viruses, and their reduced fouling tendency because of the smaller pore size, which minimizes pore-clogging risks.

MBR systems have a compact footprint and offer high-quality effluent solutions, making them suitable for meeting various wastewater treatment needs. They can be utilized to build modern, state-of-the-art facilities or upgrade existing wastewater treatment plants to improve overall efficiency and performance.

- **Membrane Clarification in Food Processing:** The scarcity of naturally pure food ingredients highlights the importance of employing separation and purification methods to ensure food safety and quality. Membrane processing has become a superior choice in certain applications due to its characteristic advantages, including low energy consumption, a reduced number of processing steps, higher separation efficiency, improved final product quality, and an eco-friendly and "cleaner" processing approach. By utilizing membrane processing, businesses can produce better quality products at a lower cost while minimizing waste generation and promoting environmental protection.

In various industries, membrane technology has become a crucial component. For example, in the food and beverage sector, membranes are employed for dealcoholising beer, achieving wine clarity, and vinegar clarification. Reverse osmosis is utilized as an alternative to traditional microfiltration and pasteurization in beer production to de-alcoholize beer before pasteurization and bottling.

In the dairy industry, ultrafiltration is primarily used to produce cheese from milk and protein concentrates from whey. During milk ultrafiltration, proteins, fat globules, and lactose are retained across the membrane, while inorganic salts, lactose,

and water are removed as permeate. This concentrated milk (retentate) is used to produce various types of cheese. In whey ultrafiltration, whey protein concentration is retained, and whey protein powder is created through spray or drum drying of the retentate. Nano filtration, on the other hand, allows for various processes such as desalting lactose, generating protein concentrates, preconcentrating thin fluids in sugar production from sugarcane and beet, and demineralizing and deacidifying whey.

Overall, membrane processing plays a vital role in achieving product purity, quality, and efficiency in the functional food and nutraceuticals industry, agriculture, dairy, food, and bioproduct industries, providing numerous benefits and contributing to environmentally friendly and sustainable production practices.

#### IV. CONCLUSIONS

Over the past few decades, membrane science and technology have significantly advanced processes and products, providing intriguing potential for developing, rationalising, and optimising novel productions. The most intriguing advancements in industrial membrane technology relate to the potential integration of diverse membrane processes into a single industrial cycle, which would significantly positively affect energy efficiency, product quality, plant compactness, and environmental impact. Potential uses for membrane engineering may also be significant in emerging fields. The most intriguing results in membrane engineering to date will be discussed, together with forecasts for the future and an analysis of the potential effects of new membrane science and technology on long-term industrial growth.

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