**Futuristic trends in advanced industrial membrane processing technologies**

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1. **Introduction**

The Latin word “membrana,” 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).

1. **Membranes and membrane processes**

In a permselective 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 permselective 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.

A diluted (aqueous or non-aqueous) solution can be concentrated or purified using various pressure-driven membrane techniques. These processes are distinguished by the solvent’s continuous phase and the relative lack of solute concentration. Different processes connected to solute particle size and, in turn, membrane structure can be identified. These procedures include 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 | Ultrafiltration | 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 /Asymmetric | Asymmetric | Asymmetric |
| Thickness of actual | Symmetric ~ 10 - 150 μm | ~ 0.1 - 1.0 μm | ~ 0.1 - 1.0 μm |
| separating layer | Asymmetric ~ 1 μm |  |  |
| Pore size | 0.05 - 10 μm | 1 - 100 nm | < 2 nm |
| MWCO | < 1,00,000 Da | 10,000 to 1,00,000 Da | 1,000 to 1,00,000 Da (NF) |
|  |  |  | 100 to 1,000 Da (RO) |
| Basis of separation | Particle size | Particle size | Differences in solubility and diffusivity |
| Application | Clarification, water treatment | Whey and protein processing, clarification, dairy, textile, pharmaceutical | Desalination of seawater, the concentration of fruit juices and milk, desolventization |

Compiled from Mulder, 1998

* 1. **Microfiltration**

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.

* 1. **Ultrafiltration**

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.

* 1. **Nanofiltration**

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 g·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.

* 1. **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.

* 1. **Gas separation**

In gas separation, a gas mixture is passed at high pressure across a membrane that only allows one component of the feed mixture to pass through; the membrane permeate is then enriched with this species. The synthesis of nitrogen from the air, the separation of carbon dioxide from methane in natural gas operations, and the separation of hydrogen from nitrogen, argon, and methane in ammonia plants are the main current uses of gas separation membranes.

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.

* 1. **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 allure of pervaporation is that the degree of separation is inversely correlated with the speed at which the constituents of the liquid mixture pass through the selective membrane. To separate closely boiled mixtures or azeotropes that are challenging to separate by distillation or other methods, pervaporation offers a solution. Additionally, methods for separating organic mixtures and removing dissolved organics from water using pervaporation are being developed.

1. **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 CO2 emissions. Membranes have a significant chance to play a significant role in all of these new technologies and transitional phases.

* + 1. **Fuel cells**

Fuel cells are the primary zero-emission energy converters used to power vehicles, portable electronics, and buildings. Fuel cells can be fueled with hydrogen or renewable fuels like methanol and ethanol. For high-temperature functioning, many proton-conducting polymer electrolyte materials have been studied. Depending on whether water is essential for proton conduction or not, two sorts of membranes can be suggested. Humidification is required to preserve the proper conductivity characteristics of polymer electrolytes (such perfluorosulfonic membranes) that involve water molecules in the proton mobility process. The operating temperature and the characteristics of the membrane affect the quantity of humidification, which affects the size and complexity of the device. Other electrolytes may not technically require humidification since the process of proton conduction in these systems does not necessarily involve water molecules. However, some drawbacks are associated with such systems’ short-term stability, including phosphoric acid leakage from the membrane. In contrast, the system is in operation, the poor extension of the three-phase reaction zone inside the electrodes due to the lack of a suitable ionomer and decreased conductivity levels for inorganic proton conductors (Tchicaya-Bouckary et al., 2002).

* + 1. **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 predominant technique utilized in hydrogen production involves steam reforming natural gas. This process entails the combination of methane and steam, followed by a catalytic reaction at elevated temperature and pressure levels (e.g., 30 to 40 bar) within the range of 700-900°C. As the reaction is governed by thermodynamic equilibrium, shift reactors (both high and low temperature) are employed to enhance hydrogen conversion. Subsequently, a preferred oxidation reactor (PreOx) and a hydrogen separator are utilized to further optimize the overall conversion of the process.

Unfortunately, the by-product of this reaction is the greenhouse gas CO2, necessitating proper treatment before being released into the atmosphere due to its environmental impact. One effective approach to enhance the total conversion of thermodynamic equilibrium-controlled reactions is through the implementation of a membrane reactor. By continuously removing one or more of the reaction products throughout the process, a membrane reactor significantly improves reaction efficiency. Thus, it is particularly well-suited for steam reforming reactions (Klette & Bredesen, 2005).

In steam reforming applications, metallic membranes, particularly those composed of Pd and Pd/alloy supported on porous metal, are particularly advantageous. These metallic membranes, along with their porous support, demonstrate excellent chemical, mechanical, and thermal stability, even at high temperatures and pressures. When compared to standalone thin films, composite membranes supported by porous metal offer the benefit of a thin membrane layer while simultaneously ensuring the necessary mechanical strength for high-pressure applications.

* + 1. **CO2 capture and power generation**

Power generation accounts for approximately one-third of the principal anthropogenic CO2 sources. Efforts to develop CO2 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:

1. Increasing energy effectiveness

2. Using low-carbon fuels or CO2-neutral or non-emitting methods for producing electricity and chemicals,

3. Creating technologies for the capture and storage of CO2.

Membranes might be crucial in the many CO2 mitigation solutions mentioned above (Powell & Qiao, 2006). The traditional methods of separating CO2 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 CO2 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 CO2/H2 selectivity was found.

Additionally, it has been demonstrated that inorganic membranes can be used with CO2 capture in a variety of fossil fuel-based power cycles. Studies comparing the efficiency of the power cycle reveal that membrane integration can absorb CO2 with a penalty of about 5–8%. Modern membranes have already shown sufficient flow and selectivity to provide methods for CO2 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).

* 1. **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.

* + 1. **Wastewater treatment**

Large amounts of wastewater are produced every day by almost every manufacturing sector (automobiles, food, steel, textiles, animal handling and processing, etc.) and service sector (hotels, transportation, etc.). Very few industries do not consume significant amounts of water, and industry makes for around a quarter of global water use. In all facets of pollution control, from end-of-pipe treatment to prevention and waste reduction, the necessity for strict pollution control (and legislation) offers a significant opportunity for membrane technology.

There are two methods for treating wastewater, depending on whether the permeate is to be recycled (for example, in alkaline/acid cleaning baths, electrocoat paint, or water) or disposed of (for instance, in machining processes, food wastes, or metal plating). However, even within the same industry and occasionally even within the same plant at different seasons of the year, the physicochemical characteristics of wastes vary greatly. Compared to most industrial membrane applications, wastewater treatment involves more thorough testing to account for potential feed-stream fluctuations, pretreatment alternatives, cleaning challenges, and problems with recycling or disposal of permeate and retentate (Cheryan, 1998).

* + 1. **Nuclear waste treatment**

A wide range of low and intermediate-level liquid radioactive wastes are produced by the nuclear industry (LRWs). These liquid wastes may be created constantly or in small batches, and their volume, radioactivity, and chemical make-up can vary greatly. In the industry, these wastes have been treated using a wide variety of treatment techniques. Most LRW treatment technologies have relied on the same traditional procedures used in the treatment of municipal and industrial water. These procedures include chemical processing, adsorption, filtration, ion exchange, and evaporation. They are limited by either their failure to remove contaminants or, in the case of evaporation, the high operating costs and considerable amounts of secondary solid waste generated, making it difficult to treat LRWs satisfactorily. The processed liquid effluent is also too impure to be recycled or released into the environment. Membrane technology has been steadily incorporated into nuclear power facilities during the last ten to fifteen years to treat low radioactive waste.

The use of membrane techniques for the treatment of liquid radioactive wastes necessitates the resolution of numerous issues relating to the appropriate selection of membranes, membrane modules, and other equipment according to local conditions, including the chemical and radiochemical composition of the treated effluents, their activity, and their total salinity.

By passing only a portion of the stream across a membrane, membrane procedures allow radioactive contaminants to be removed from the waste stream. Depending on the size of the pore in the membrane, these techniques include reverse osmosis (RO), ultrafiltration (UF), and microfiltration (MF). Membrane techniques have already been used to clean up boric acid solutions for recycling, mixed laboratory wastes, and radioactive laundry wastes in nuclear power plants. Numerous membrane-based installations are effectively used in the nuclear sector.

A new technique called membrane distillation (MD) has recently been introduced. Membrane distillation is a separation technique that uses a porous, liquid-unwettable liophobic membrane. Due to the polymer’s liophobicity, only vapour may pass through membrane pores. Condensation occurs on the membrane’s opposite side, in an air gap, a cooling liquid, or an inert carrier gas. Hydrophobic membranes made of polymers like polypropylene (PP), polytetrafluoroethylene (PTFE), or poly(vinylidenefluoride) (PVDF) are utilised in the process because MD is typically used to treat water solutions. A gradient of the solution’s component partial pressures in the gaseous phase is the driving force behind the MD process. Despite some technological and procedural restrictions, membrane procedures are particularly effective ways to treat various types of effluents. The most recent uses of membrane technology in the field of radioactive materials processing industries include the removal of tritium from nuclear waste (liquid and gaseous effluents), isotope separation, gaseous radioactive wastes, and noble gases separation (Zakrsewska-Trsnadel et al., 2001).

* + 1. **Air pollution**

The most common sources of air pollution are industry, power plants, automobile transportation, and municipal and agricultural trash. The release of so-called acid gases (SO2, NOX), volatile organic chemicals, primarily halogen-derived hydrocarbons, and aromatic compounds, which deplete the ozone layer and contribute to the greenhouse effect, makes pollution especially dangerous. These chemicals are removed using a variety of techniques. Specific strategies have been categorised based on the ideal level of focus at which they function. From an economic and technical perspective, properly mixing different processes (hybrid processes) can be advantageous. The removal of volatile organic compounds can be done with or without solvent recovery, but the second option is preferred from an environmental and financial standpoint (Bodsek, 2000).

The production of large quantities of gases that contribute to the greenhouse effect, such as carbon dioxide when burning fuels generated from carbon, and simultaneous emissions of methane and carbon dioxide from solid waste dumps, is another issue associated with atmospheric pollution. Regarding the latter scenario, it appears advantageous to recover methane because it is a valuable energy source with a higher global warming potential than carbon dioxide.

The idea of gas separation via membranes is based on the dissolution and diffusion mechanisms. Gases typically have a low solubility in polymers (about 0.2%) because they have a lower affinity for polymers than liquids. When a polymer’s affinity for a certain gas increases, so does the gas’s solubility; for instance, carbon dioxide is more soluble in hydrophilic polymers than in hydrophobic ones.

* 1. **Hybrid processing employing membranes for industrial applications**
     1. **Nano-composite gas separation membranes**

Simple and inexpensive membrane gas separations are appealing but frequently constrained by insufficient gas flux. This issue is challenging because a material’s permeability and selectivity are typically inversely correlated. Recently developed polymer-inorganic nano-composite materials have been created to enhance the physical characteristics of polymer membranes. Two matrices—a polymer and an inorganic substance—combine to form the polymer-inorganic nano-composite membrane. The inorganic phase is scattered at a nanoscale level in the polymer phase of these membranes. The unique structural features of polymer-inorganic nano-composites enhance the gas separation properties of pure polymers.

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).

* + 1. **Separation of light hydrocarbons**

Solutions, mixes of substances with similar boiling points, and aseotropes that are challenging to separate by distillation or other techniques can all be separated by pervaporation. At American Oil, research on pervaporation was initially conducted systematically in the 1950s. In the 1950s, American Oil conducted the first comprehensive study of pervaporation. The method was not commercialised at the time and remained a mild academic curiosity until 1982 when the first commercial pervaporation plant was erected by GFT (Gesellschaft für Trenntechnik GmbH, Germany).GFT later erected more than 50 similar plants; the first of these facilities were used to extract water from concentrated alcohol solutions. Polyvinyl alcohol is used in these plants as composite membranes since it is far more permeable to water than alcohol.

Separating water from organics during commercial pervaporation is another procedure. Organic solvents and water have highly different polarities and display different membrane penetration characteristics, making this separation very simple. Separating methanol from methyl t-butyl ether/isobutene mixtures, the first pilot-plant result for an organic-organic application was announced by Separex in 1988. The cellulose acetate membranes that are currently available perform well in this application, which is very advantageous. Exxon recently began a pervaporation pilot plant employing polyimide/poly urethane block copolymer membranes to separate aromatic/aliphatic mixtures. One of the main separating issues in refineries is this separation (Baker, 2000).

* + 1. **Solvent dewaxing**

Separating organic/organic mixtures is a possible new use for reverse osmosis in the chemical sector. These separations are challenging because of the large osmotic pressures that must be overcome and the need for membranes that are solvent resistant enough to be mechanically robust and permeable enough to get good fluxes.

The oil industry eliminates waxes through chilling, settling, and separating. The traditional pressure leaf filter used in the refinery had problems clogging the filter media, getting neutral oil trapped in the filter earth, and disposing of it. These issues have been lessened with the introduction of the centrifugal technique. This strategy calls for a polish filtration phase to guarantee low wax concentrations in processed oils. Some of the issues as mentioned above with industrial operations could be solved by membranes, and attempts have been made using hexane-diluted and undiluted vegetable oils using UF and microfiltration (MF) membranes, respectively (Subramanian et al., 2021).

The research indicated that the MEUF approach was efficient in simultaneously degumming and dewaxing hexane-diluted oils without needing a precooling step, providing a method that will result in significant energy savings. In contrast, the MF membranes were very effective for dewaxing undiluted oils but with a precooling step. Additionally, this method offers the advantages of a one-step pretreatment, lowering the burden of contaminants in the subsequent steps of membrane refinement.

* + 1. **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.

* + 1. **Membrane aromatic recovery system**

Membrane methods have garnered interest regarding the removal of low-volatility organics from wastewaters. To recover organics from aqueous solutions, membrane solvent extraction has been utilised with porous membranes. However, porous membranes have a significant drawback because of their instability. Unless sufficient breakthrough pressure through the membrane is maintained, the immobilised phase in the pores can be breakthrough. It was suggested to use nonporous membranes for extraction. Nonporous membranes have a substantially higher breakthrough pressure than porous membranes, but at the expense of a slower mass transfer rate during membrane extraction.

It has also examined how membrane technology might be used to prepare extracts of bioactive spices. The volatile constituents preferentially permeated through the SRNF membrane, increasing their content from 75 to 97.8% while rejecting the nonvolatiles, matching the quality of direct steam distilled oils in an experiment with turmeric oil extracted from curcumin-removed-turmeric oleoresin (Gopika & Subramanian, 2020). In contrast, the SRNF membrane showed increased rejection of rosmarinic acid (Ro-99.7%) and caffeic acid (Ro-93.9%) in research with rosemary extract in the ethanol phase (Peshav et al., 2011), resulting in their concentration in the retentate fraction.

* + 1. **Membrane bio-reactor**

Membrane bioreactors are a technology for wastewater treatment that may offer various benefits over traditional biological processes alone. The combination of two fundamental processes, biological degradation and membrane separation, is known as a membrane bioreactor (MBR). Activated sludge is a biological process frequently used with membrane technology for wastewater treatment. Most MBR systems now in use are utilised to treat wastewater from various industries, including food and beverage processing, metal fabrication, automotive, cosmetic, and landfill leachate (Muhamad et al., 2021).

A bioreactor is a container created explicitly for the wastewater treatment process to sustain a biologically active environment where bacteria and protozoa (the so-called biomass) can grow and consume some (or all) of the constituents of the raw wastewater. Depending on the absence or presence of oxygen and nitrates, they can be aerobic (to remove organic matter and oxidise ammonia to nitrate), anoxic (to remove nitrogen from nitrates to nitrogen gas), or anaerobic (to remove organic matter). Membranes are typically constructed following aerobic or anaerobic bioreactors.

Membranes serve as a solid-liquid separation mechanism in the MBR process, keeping the biomass inside the bioreactor before releasing the treated effluent to the environment. They replace the clarifiers used in the standard activated sludge (CAS) process. MBR applications can employ micro- (MF) and ultrafiltration (UF) membranes. UF membranes are typically the best option due to their greater separation properties (allowing them to remove certain colloids and viruses as well) and reduced tendency to foul (because of the smaller pore size, they have a lower risk of pore-clogging).

MBR’s low-footprint, high-effluent solution can satisfy your wastewater treatment needs. It can be utilised to construct brand-new, cutting-edge facilities and upgrade current wastewater treatment plants.

* + 1. **Membrane clarification in food processing**

The fact that few naturally pure food ingredients are available emphasises the significance of various separation and purification methods in converting food or food substances into safe and direct consumable form. Due to its characteristic advantages, such as low energy consumption, fewer and gentler processing steps, greater separation efficiency, improved final product quality, eco-friendly and “cleaner” processing, i.e. better quality products at lowest cost with highest environmental protection through minimal/low waste generation, membrane processing is superior to other conventional methods in certain applications. These procedures are now a crucial component of a variety of businesses, including the functional food and nutraceuticals industry, the agricultural, dairy, food, and bioproduct industries (Reig et al., 2021).

Membranes are employed in this field for dealcoholising beer, wine clarity, and vinegar clarification. Reverse osmosis is used as an alternative to traditional microfiltration and pasteurisation in the traditional beer production process to de-alcoholise beer before it is pasteurised and bottled. In the dairy sector, ultra filtration primarily produces cheese from milk and protein concentrates from whey. In the ultrafiltration of milk, proteins, fat globules, and lactose are kept across the membrane while inorganic salts, lactose, and water are removed as permeate. This concentrated milk (retantate) produces many different types of cheese. Whey protein concentration is kept across the membrane during whey ultrafiltration. Whey protein powder is created by spraying or drum drying this retentate. The desalting of lactose, the generation of protein concentrates, the preconcentration of thin fluids in the manufacturing of sugar from sugarcane and beet, and the demineralisation and deacidification of whey derived through ultra filtration are all possible with nano filtration.

1. **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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