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

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1. **Introduction**

The Latin word "membrana," which meaning "skin," is where the word "membrane" originates (Jones, 1987). A thin flexible sheet or film that serves as a selective boundary between two phases due to its semi-permeable qualities is now referred to as a membrane. A membrane can be either solid or liquid physically. It serves as a highly selective separation agent based on differences in diffusivity coefficient, electric current, or solubility. In actuality, membrane is now an essential component of our daily lives. All living cells, including those in us, are encased in a membrane. Membrane cells in living things are extremely 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 byproduct 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), as well as chemical process industries, also use membrane technology (organic separation, gas separation, recovery and recycle 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 deionization).

1. **Membranes and membrane processes**

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 certain 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.

Transport across a membrane can be active or passive, driven by a variety of factors (such as pressure, concentration, or electrical difference), and can be 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. For solid synthetic membranes, there are two different types of membrane structures: symmetric and asymmetric (anisotropic).

Because the membrane and the permeating components have different physical and/or chemical properties, the membrane can carry some components more easily than others. A driving force acting on the feed's components causes them to move across the membrane. Gradients in pressure, concentration, electric potential, or temperature can all act as driving forces. The membrane itself is the primary determinant of selectivity and flow in addition to the pushing force. The sort of application, which can range from the separation of microscopic particles to the separation of molecules of the same size or shape, is actually determined by the nature of the membrane.

A diluted (aqueous or non-aqueous) solution can be concentrated or purified using a variety of pressure-driven membrane techniques. These processes are characterised by the continuous phase of the solvent and the comparatively low solute concentration. Different processes that are 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 2 Comparison of pressure driven membrane processes**

|  |  |  |  |
| --- | --- | --- | --- |
| Paramaters | 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 sea water, 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 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 blood for therapeutic and commercial uses, MF processing is extensively employed in the food industry. Applications including cell recycling and harvesting, separating recombinant proteins from cell detritus, and stream purification are all examples of MF in the biotechnology sector.

* 1. **Ultrafiltration**

Ultrafiltration membranes are mostly employed for fractionating, or separating high-molecular-weight solutes from low-molecular-weight solutes. When compared to reverse osmosis membrane systems, ultrafiltration membranes require substantially lower hydraulic pressures as a driving force since they have bigger pore diameters.

* 1. **Nanofiltration**

A pressure-driven membrane process is nanofiltration. Nanofiltration employs lower pressures and filters with greater pore sizes than reverse osmosis. It is a pressure-driven membrane method that is commonly used to remove solutes from aqueous streams with molecular weights between 200 and 1000 g·mol-1. The application of organic solvents to nanofiltration techniques is a new breakthrough known as organic solvent nanofiltration (OSN). OSN is a topic of intense research at the moment. Nanofiltration has great promise for the separation of molecules found in organic solvents in a variety of industries, including precision chemical and pharmaceutical production.

* 1. **Reverse osmosis**

Virtually no solute species, organic or inorganic, travel across RO membranes into the permeate except for the solvent. The methods of separation involve interactions between the species and the membrane as well as shape, size, and ionic charge. It is a green technique used for wastewater recovery for reuse, groundwater purification, and boiler feed water treatment. Despite the technology's widespread use, it is nevertheless constrained by the significant osmotic pressures that seawater or effluents with high total dissolved solids exert.

* 1. **Gas separation**

In gas separation, a gas mixture is passed at a 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 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.

* 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. In order 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 a significant and adaptable method in our daily lives. The globe faces more difficult 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 a range of 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, a variety of 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 being encouraged to modernise in order 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 required 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, there are some drawbacks associated with the short-term stability of such systems, including phosphoric acid leakage from the membrane while the system is in operation, poor extension of the three-phase reaction sone 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 is almost certain to 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 very small 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 most widely utilised method for producing hydrogen is by far steam reforming of natural gas. Methane and steam are combined during steam reforming, and a catalytic reaction is carried out at a high temperature and pressure (e.g., 30 to 40 bar) (700-900°C). Because the reaction is governed by thermodynamic equilibrium, shift reactors (high and low temperature) are employed to improve the hydrogen conversion, followed by a preferred oxidation reactor (PreOx) and a hydrogen separator, in order to boost the overall conversion of the process. Unfortunately, the reaction's by-product is the greenhouse gas CO2, which needs to be treated because it cannot and should not be released into the atmosphere. By continually eliminating one or more of the reaction products throughout the reaction, a membrane reactor can boost the total conversion of a thermodynamic equilibrium-controlled reaction. As a result, it is particularly well suited for performing the steam reforming reaction (Klette & Bredesen, 2005). For the steam-reforming application, metallic membranes, in particular Pd and Pd/alloy membranes supported on porous metal, are ideally suited. At high temperatures and pressures, both metallic membrane and porous support are chemically, mechanically, and thermally stable. In comparison to standalone thin films, composite membranes supported by porous metal have the benefit that a thin membrane layer can be created since the porous support offers the essential mechanical strength for high pressure applications.

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

Power generation accounts for about one-third of the primary anthropogenic sources of CO2. Efforts to create technology for CO2 reduction have been motivated by the growing agreement that this emission contributes to an increase in the global temperature with tremendous potential implications. 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 the production of materials for membranes with preferential CO2 transport. The use of polymers containing segments made of ethylene oxide is a method that is being researched by various parties. 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 to be crucial for the features of current membranes. 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.

* + 1. **Wastewater treatment**

Large amounts of wastewater are produced everyday by almost every manufacturing sector (automobiles, food, steel, textiles, animal handling and processing, etc.) and service sector (hotels, transportation, etc.). There are very few industries that 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 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. The majority of LRW treatment technologies have relied on the same traditional procedures used in the treatment of municipal and industrial water. Chemical processing, adsorption, filtration, ion exchange, and evaporation are a few examples of these procedures. They are constrained by either their inability to completely remove impurities or, in the case of evaporation, the high running expenses required and the significant amounts of secondary solid waste generated, making it challenging 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 waste stream. Depending on the size of the pore in the membrane, these techniques include reverse osmosis (RO), ultrafiltration (UF), and micro filtration (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 takes place on the opposite side of the membrane, 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 acts as the driving force behind the MD process. Membrane procedures are particularly effective ways to treat various types of effluents, despite some technological and procedural restrictions. 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, the proper mixing of different processes (hybrid processes) can be advantageous. The removal of volatile organic compounds can be done with or without solvent recovery, but from an environmental and financial standpoint, the second option is preferred (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 and has 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 do. 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 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 they are frequently constrained by insufficient gas flux. This issue is particularly difficult because a material's permeability and selectivity are typically inversely correlated. To enhance the physical characteristics of polymer membranes, recently developed polymer-inorganic nano composite materials have been created. 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 gas separation properties of pure polymers are enhanced by the unique structural features of polymer-inorganic nano composites.

The inorganic nanofillers are typically spread in a continuous polymer matrix, and the nanocomposite 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 nanocomposite membrane. Nanocomposite membranes have several novel features not found in polymeric or inorganic membranes thanks 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. The first commercial pervaporation plant was established in 1982 by GFT (Gesellschaft für Trenntechnik GmbH, Germany), after the process had not yet been commercialised and remained primarily an academic interest. GFT later erected more than 50 similar plants; the first of these facilities was 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. The separation of 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 to the large osmotic pressures that must be overcome and the need for membranes that are both solvent resistant enough to be mechanically robust and permeable enough to get good fluxes.

In the oil industry, waxes are eliminated through a process of chilling, settling, and separation. The traditional pressure leaf filter used in the refinery had problems with clogging the filter media, neutral oil getting trapped in the filter earth, and disposing of it. These issues have been lessened with the introduction of the centrifugal technique. To guarantee low wax concentrations in processed oils, this strategy calls for a polish filtration phase. Some of the aforementioned issues 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 in this area indicated that the MEUF approach was efficient in simultaneously degumming and dewaxing hexane-diluted oils without the need for 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 goes through several refinement procedures to get rid of 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 process 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 has become one of the main areas for membrane applications because there is such a huge potential for energy savings as well as 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. Using porous as well as nonporous denser polymeric composite membranes, several researchers have attempted the membrane processing of edible oils with and without solvents.

Whilst membrane technology might be used at several phases of the oil processing process, the solvent recovery step has the greatest potential for energy savings. The creation of a membrane that is resistant to solvents and has the ability to separate hexane from the hexane-oil miscella could lead to significant 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**

Regarding the removal of low-volatility organics from wastewaters, membrane methods have garnered interest. For the recovery of organics from aqueous solutions, membrane solvent extraction has been utilised with porous membranes. However, porous membranes have a significant drawback because of their instability, which is that unless a sufficient breakthrough pressure through the membrane is maintained, breakthrough of the immobilised phase in the pores can happen. 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 been looked at 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 a 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 that is frequently used with membrane technology for wastewater treatment. The majority of MBR systems now in use are utilised to treat wastewater from various industries, including the food and beverage processing, metal fabrication, automotive, cosmetic, and landfill leachate (Muhamad et al., 2021).

A bioreactor is a container specifically created 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 presence or absence 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 essentially replace the clarifiers that are used in the standard activated sludge (CAS) process. MBR applications can employ both 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).

Your wastewater treatment needs can be satisfied with MBR's low-footprint, high-effluent solution. It can be utilised to construct brand-new, cutting-edge facilities as well as to 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 inherent 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 being employed in this field for dealcoholizing 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-alcoholize beer before it is pasteurised and bottled. In the dairy sector, ultra filtration is primarily used to produce 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. Many different types of cheese are made using this concentrated milk (retantate). 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 demineralization 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 both processes and products, providing intriguing potential for the design, rationalisation, and optimization of 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 have significant positive effects on 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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