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Membrane-Based Processes for Water Treatment and Desalination: A Comprehensive Review

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Abstract

Recently, research on new and developed methods of water desalination and water treatment has become more important, due to the excessive need for freshwater for municipal, agricultural, and industrial purposes. Due to the lack of drinkable fresh water, water desalination methods based on membranes are developing continuously. In this article, membrane-based processes for water desalination are reviewed. This includes but is not limited to electrodialysis, electrodialysis reversal, membrane distillation, pervaporation, reverse osmosis, and forward osmosis. Also, membrane fouling methods and the applied processes for controlling (cleaning) fouling are discussed in detail. This includes physical cleaning by periodic back flushing, pneumatic cleaning, ultra-sonic cleaning or sponge ball cleaning, chemical cleaning, biological/biochemical cleaning or physico-chemical cleaning. Types of membranes are reviewed. Moreover, inorganic membranes (IM) are compared to organic membranes (OM). Generally speaking, IM have much better characteristics, such as relatively high chemical resistance, long lifetime, good thermal and mechanical stability, and autoclavable, making them suitable for use in harsh conditions such as corrosive and high-temperature environments. Furthermore, the manufacturing of IM does not consume toxic solvents. However, the marketing of IM is still small, and its prices are still expensive. IM can be developed by doping with nanomaterials such as graphene oxide.

Keywords: Water desalination; Electrodialysis; Membrane distillation; Forward osmosis; Reverse osmosis; Membrane fouling; Membrane cleaning.

1. Membrane-Based Processes for Water Desalination

The main membrane function is acting as a barrier for selectively preventing certain components from passing through it, thus dividing two phases from one another [1]. Since the 18th century, membranes have been around. Subsequently, substantial progress has been made in rendering membranes increasingly appropriate for an array of uses [2]. The type of material affects the form and process of separation of the resultant membrane. The process of choosing a material for membrane preparation is not haphazard; rather, it is guided by the material's defined properties, which are derived from its structural features as well as its chemical and physical makeup. The following variables affect the choice of material [3,4]:

- material selectivity and permeability,
- chemical resistivity,
- mechanical rigid,
- thermal resistance,
- economic and engineering feasibility.

Membranes fall into two main groups, as shown in Fig. 1, according to their cross-section and the material used to make them. Isotropic and anisotropic membranes make up the two groups that comprise the first class of membranes. Isotropic membranes are composed entirely of a single component and have a homogeneous structure. Three forms of isotropic membranes are distinguished: electrically charged membranes, nonporous dense films, and macroporous membranes. Membranes with holes of varying sizes, referred to as microporous membranes or screening membranes, are used to separate out solutes. They have pores that can have a diameter of 0.1 to 5 µm [5,6] Pressure, chemical reagents concentrations, or electric field gradients are applied as relatively driving forces for solutes transportation which is controlled by transportation rate, while diffusion is driven by the concentration difference on either side of the membrane [7].

Membranes that are electrically charged and referred to as anion/cation exchange membranes have surfaces that have been enhanced by either positive or negative size of pores as well as the thickness vary from place to place [9].

As an alternative, composite membranes such as thin-film membranes have a variety of chemical compositions and structural elements. The thin layer on top of thin film membranes is accompanied by a significant porous support made of polymeric material. The surface layer thickness, as well as porosity and pore size, and other characteristics, govern solute transport across thin film membranes [10].

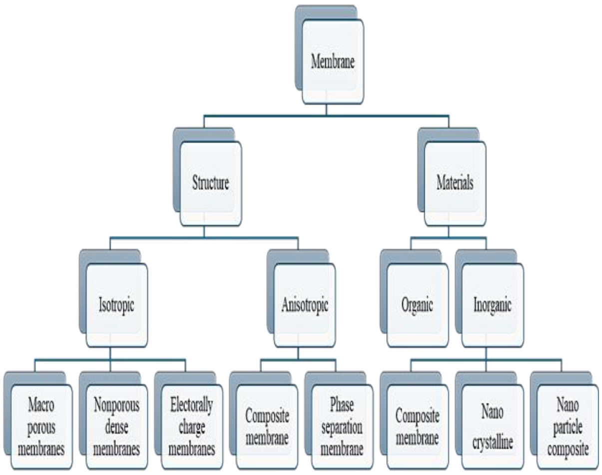

Fig. 1. Types of Membranes

Membranes can be either inorganic or organic (polymeric), depending on the material used in their creation. In contrast to inorganic membranes, which include but are not limited to ceramics, nonporous carbon, zeolites and amorphous silica, organic membranes include polysulfone, polyether sulfone, cellulose acetate, polymethyl pentene, polyimide, polyetherimide, polycarbonate, polydimethylsiloxane, and polyphenylene oxide [11].

ions. Either microporous structures or thick, nonporous sheets make up their composition. Both solute ions concentration and solute charge density control the transport mechanism in these membranes [8].

Conversely, anisotropic membranes exhibit heterogeneity with respect to their structural makeup and chemical composition. Anisotropic membranes can be further divided into composite membranes, which comprise thin-film, coated films, and self-assembled structures, and phase-separation membranes (also known as Loeb-Sourirajan membranes). Although phase separation membranes are chemically homogeneous, however, the structure, the porosity, the

Compared to organic membranes, molecular sieve membranes have greater resistance against some harmful chemicals such as solvents of organic nature and chlorine. This is particularly helpful in applications involving the treatment of water with these harmful chemicals that could harm the membranes of organic nature. Chemical resistance also makes it possible to regularly clean and wash inorganic membranes using a variety of anti-scaling solutions as well as different kinds of solvents. Moreover, membranes of inorganic nature possess mechanical strength and are impervious to microbiological assault. Although polymeric membranes have several drawbacks, like fouling and instability at high temperatures, their use is growing, especially in the technology of desalination as well as technology of water treatment. Therefore, there are currently significant research and development efforts being done to create membranes of inorganic nature. While these membranes are more costly than membranes of organic nature, they have various benefits, such as resistance to high temperatures and wear (up to 500 °C), high chemical and pore structure stabilities and long life time. They can also tolerate frequent backwashing, sterilization, and autoclaving. However, their rigidity and expensive cost are the main drawbacks [12]. Table 1 provides a comparison between organic and inorganic membranes in terms of their material characteristics, advantages, and disadvantages.

The membrane needs to be strong to the exposed separation conditions in water purification applications. Furthermore, the membrane needs to be very stable and mechanically stiff against applied driving force. To extend the life of membrane materials, they must be environmentally friendly. Typically, feeding streams are polluted with a variety of components such as but not limited to oils and solvents of organic nature, which can swell or dissolve or damage the materials of membrane. To protect the damage of the membrane and enable it to endure high feed operating temperatures, temperature stability is also essential. The last twelve years have seen a notable advancement in membrane material technology. Numerous research projects have been carried out to investigate different kinds of materials and their architectures that have many applications. The synthesis of membranes can be classified as either organic (polymeric) or inorganic depending on the material utilized. In addition, inorganic membranes contain but not limited to metals, or oxides etc. in their structure. The membranes of organic nature are made of nonporous polymeric materials [15].

Table 1: Comparison between Organic and Inorganic Membranes

Properties	Inorganic Membranes	Organic Membranes
Material	Inorganic materials i.e. ceramic, hydroxyapatite, glass and carbon etc.	Rubber,polymers and glass type membranes.
Characteristic	Chemically and thermally stable, mechanically strong, and capable of operating in extreme feed conditions.	Rigid in a glassy form, but flexible in a rubbery state.
Advantages	*Ability to withstand harsh chemical conditions. *Sterilization and autoclaving at high temperature up to 500°C. * Wear resistance, stable pore structure, excellent chemical stability, and extended lifetime.	Cost effectiveness, high selectivity, and simple process capability.
Disadvantages	May be stiff and brittle	Chemical fouling, limited operating temperature & pressure, and short lifetime.
Ref.	[13]	[14]

1.1. Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Ion-permeable membranes and electricity are used in the electro-dialysis (ED) and reverse electro-dialysis (EDR) procedures to remove dissolved ions from water. These procedures transfer ions through an ion-permeable membrane from the dilute solution to the concentrated one electric voltage [16].

Two different kinds of ion exchange membranes are used in electrodialysis. One membrane is permeable to the anions and cations. The other one is permeable to anions. So, two streams of solutions are generated. The diluted feed ions as well as the concentrated feed ions individually transfer from the dilute into the concentrate through oppositely charged membranes (the anions to the anode and the cations to the cathode) when an electric current pass through the system. The anion-exchange membrane of positively charged (AEM) retains the cations. Furthermore, anions are retained by the cation-exchange membrane (CEM). As a result, there is an ion-rich concentration stream and an ion-depleted input stream [17,18].

EDR is the electrodialysis reversal of the membrane's electrodes, which reverses the transport of ions. This reduces membrane fouling by diluting concentrated flows and increasing the concentration of diluted flows [19]. ED and EDR have been used in numerous wastewater treatment applications.

When it comes to the removal of ionized component particles and total dissolved solids (TDS), ED and EDR are particularly useful in wastewater treatment. Extremely high-water recovery rates are provided by ED and EDR, and little preparation of the supply of water is required. Less membrane fouling is the outcome of the process reversal, and the method is compatible with renewable energy sources [20]. However, because desalination energy is correlated with the number of ions removed, ED is not appropriate for high-salinity wastewater streams. Operating this would be incredibly costly. Additionally, non-ionized substances or molecules that pose a special risk, such as germs and viruses, are not eliminated by the process. This implies that a post-treatment is necessary, which drives up the process's cost. Moreover, the anode's production could lead to corrosion [21, 16-18]. One of the most important factors affecting the movement of particles in the film is the roughness of the film, as shown in [22]. The results show that roughening the CNT duct increased the primary fluid-duct force. Using an armchair-edged CNT structure enhanced sample's electric current. The roughness increased the gravity-induced force in the channel, reducing fluid particle mobility. The rougher duct sample had more broken hydrogen bonds inside the simulated box, from 116 to 128. There are many applications of Electrodialysis (ED) and Electrodialysis Reversal (EDR) technology, the most important of which are: The removal of ammonium and ammonia from wastewater. The results indicate the viability of low-energy TAN removal from actual reject water derived from sludge anaerobic digestion utilizing the SEDR + BPC configuration [23]. Also, application product of water and hydrogen at same times [24]. The current study pertains to an electrodialysis system that is designed to produce hydrogen at the cathode of the apparatus in addition to desalinating brackish water.

1.2. Membrane Distillation (MD)

There are currently just a few commercial applications for membrane distillation, a water desalination membrane technique. Reverse osmosis (RO) and distillation are combined in membrane distillation, which allows water vapor to pass through the membrane pores without enabling solutions to form. The membrane is synthetic and hydrophobic. The pressure differential across the membrane is the vapor pressure differential of the liquid [25] by using a temperature differential across the membrane, membrane distillation (MD) removes water from a brine solution and condenses a clear condensate on the cold side. (MD) is a new membrane technology under investigation. This hybrid membrane technology is believed to have existed for around 50 years, but there hasn't been much progress toward its commercial or broad use [21]. Membrane distillation is the technique of employing heat to separate compounds based on their volatility. This technique transfers water vapor through a hydrophobic microporous membrane using a vapor pressure gradient [28]. This heat-driven technique is highly effective at separating feed solutions with a high water content. MD is made to generate the necessary vapor pressure differential between the feed and product sides of the membrane using low-grade heat energy (less than 100 °C) [29].

When MD was used to treat generated water from the Arabian Gulf region, for example, it showed great promise in terms of permeate flux and energy consumption [30]. Wastewater from table olives that was high in phenolics was treated with MD. Membranes with different pore sizes were used to evaluate the effect on phenol concentration and penetration quality [31]. Conductivity readings below 193 $\mu S.cm^{-1}$ and phenolic amounts below 16 mg of TYE/L (tyrosol equivalent per liter) demonstrated the product's good quality. In terms of temperature polarization, purity, and distillate flux, the energy efficiency of an MD system in the treatment of textile wastewater was investigated [32]. Their results suggest that increasing the pushing force applied to the membrane can increase MD's energy efficiency. They discovered that MD could be used to purify textile effluent and gather high-quality water for later use. MD membranes should have a low barrier to mass transfer so that mass can flow freely. To maximize heat maintenance in the system, the membrane material must have a low thermal conductivity. A membrane for MD must likewise have a low affinity for water in order to avoid excessive membrane wetting. Pore diameters typically fall between 0.1 and 1 μm [33]. There are many fascinating opportunities in MD. It is possible to use renewable energy sources like wind and solar electricity. Utilizing recovered waste heat from industrial processes is another option. Compared to reverse osmosis (RO), MD requires less hydrostatic pressure. For example, working pressures that are nearly equal to atmospheric pressure can be employed with MD. Once more, compared to pressure-driven membrane processes, membrane fouling is decreased due to the increased pore size requirements. 100% separation of nonvolatile from volatile components is achieved through feed product separation. The concentration of pollutants has no effect on the quality of the product [34, 35]. Despite the benefits listed above, MD has many disadvantages. First of all, without usage history, the cost of producing water is uncertain. Second, the lack of membranes made, especially for MD puts the process in grave danger when membranes used for other procedures are used. This could lead to membrane moisture, which encourages organic buildup and necessitates comprehensive pretreatment. This raises the total cost of the process [34,35]. Finally, simultaneous mass and heat transport leads to a fluid boundary layer and temperature polarization (TP).

Temperature polarization is primarily caused by temperature differences between the bulk of the feed and the feed-membrane interface, where water evaporates, as well as between the permeate and the permeate itself and the permeate-membrane contact, where condensation takes place. This temperature polarization inhibits the driving force, reducing the permeate flux [36]. Some researchers are working on improving the efficiency of membrane distillation, which provides valuable insights into improving the flow and energy efficiency in membrane distillation applications by coating fatty materials such as stearic acid on the surface of commercial membranes such as PTFE and PVDF [37]. Also, some researchers are working on connecting a thermoelectric device to an air gap membrane distillation (AGMD) unit to efficiently desalinate brackish water [38]. There are some studies that combine SGMD unit with a two-stage vertical bubble dehumidifier (BCD). The initial stage of BCD uses room temperature environmental water for dehumidification purposes, while the later stage uses chilled water. The proposed new system has lower energy consumption compared with the traditional system [39].

1.3. Pervaporation

This method uses membrane permeation and evaporation to separate liquid mixtures based on preference, as shown in Fig. 2 [40]. The liquid combination is applied to one side of the membrane, and the permeate is evaporated on the opposite side [24]. During this phase, the permeate undergoes sorption upstream. Thus, the more porous part of the liquid mixture adheres to the membrane (either a nonporous polymeric membrane or a molecularly porous inorganic membrane). These components then diffuse through the membrane and evaporate at its downstream phase as a result of a diffusing species concentration difference. After condensing, the vapor is then recovered as a liquid. The solution-diffusion model of mass transfer over the membrane is used to demonstrate it [41].

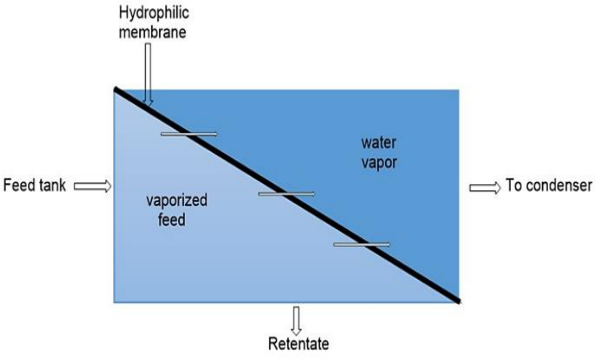

Fig. 2. Membrane Pervaporation [41].

The primary application of this technique has been the extraction of ethanol from water [42]. Nonetheless, it is being investigated for wastewater treatment in some businesses. Through evaporation, wastewater was utilized to micro-water plants. During the experiment, a thick hydrophilic pervaporation barrier was placed in specific areas of the soil [43]. To observe the permeation flow and reject impurities, synthetic wastewater was cycled through the membranes in a feed tank. The findings suggested that this method could affect the treatment of brackish groundwater or wastewater for micro-irrigation.

In a pilot-level operation, organic solvents (benzene, toluene, naphtha, butane, ethyl ether, and so forth) were extracted from diluted aqueous streams, [31]. These solvents were extracted from an aqueous stream and concentrated using 100 organophilic membranes. Organic solvents have been shown to concentrate at least 50–100 times, resulting in a cleaner effluent stream that can be disposed of or reused [44]. In a related study [45], A polyether block amide (PEBA) membrane that is selective for aromatic hydrocarbons was used to extract phenol from industrial effluent that was discharged from a phenolic resin process. Up to 10% phenol and other contaminants were present in the wastewater. According to the examinations, the phenol levels were below 300 mg L^{-1}.

Pervaporation's special characteristics make it ideal for target-specific contaminants. Pervaporation membranes are specifically designed to have a stronger affinity for the material to be separated due to their specialized application. This illustrates how the form and composition of the membrane play a crucial role in achieving the necessary separation [46]. Temperature, feed flow velocity, partial pressure, and feed concentration are other variables that affect pervaporation processes [47].

Pervaporation is recognized as an energy-efficient, ecologically friendly approach that can successfully separate liquid mixtures when traditional separation techniques are insufficient [48]. There are certain drawbacks to this approach. Large industrial applications have not yet been realized due to the extremely delicate operating conditions. Again, the utility of pervaporation beyond dehydration is limited by the high cost and limited availability of certain membranes [49].

One of the most important drawbacks facing this process is the high cost of energy and membranes required for this process. One of the most important studies that addressed the main axis in membrane production [50, 51].

1.4. Nanofiltration (NF)

In nanofiltration, membranes with pore diameters ranging from 0.5 to 2 nm and operating pressures between 5 and 40 bar are employed. NF is used while working with sugars, organic chemicals, and multivalent salts in solutions. A charged nanofiltration membrane rejects negatively charged ions like phosphate and sulfate. Non-charged nanofiltration membranes reject uncharged ions and dissolved materials according to the size and shape of the molecule; positively charged ions are rejected according to the membrane fouling process and membrane charge [52, 53]. Figure 3 shows a schematic diagram illustrating the nanofiltration process.

NF membrane was first applied as a separating membrane system in the 1980s, mostly for softening and organic removal, even though its application dates back to the late 1970s. The use of NF membranes increased during the 1990s. Since then, there has been a substantial expansion in the applications of nanofiltration membranes. Huge NF membrane-using plants were built in the 1990s, such as the 140,000 m3/day permeate Mery-sur-Oise facility in France [54].

Many membrane manufacturers create NF membranes. Membrane materials can be made more permeate-fluid, less retentive, and have larger membrane pores by using polymers such as polyether-sulfones, aromatic poly (acrylonitrile), polyamides, and poly (phenylene oxide) and its derivatives. NF membranes are composed of an active skin layer that controls the separation properties and a framework that reinforces the porous layer and increases the membrane's mechanical strength. The membrane skin layer produced by "phase inversion" (immersion precipitation) has the potential to adhere to the supporting structure indefinitely. The active surface layer of these membranes has unique nanometer-sized holes. Furthermore, the skin layer can be viewed as an additional layer of coating on a support system that has been particularly constructed. The TMC and hybrid models assumed a solid skin layer, but the space-charge and Donnan-Steric Pore models (DSPM) assumed a porous skin layer. The models were used to predict the material rejection of NF membranes [52-54].

The NF method is widely used in many industries, such as drinking water and wastewater treatment. Reducing NF's energy consumption can be achieved by optimizing factors including pH, pressure, and temperature. Many researchers have examined the impact of operating temperature on the passage of neutral solutes and water over NF membranes. Operational parameters and energy consumption have a direct effect on mass transmission and pressure decrease. The NF technique was used for streams in the temperature range (T > 50°C) as opposed to NF at standard temperatures (T 25°C). The separation process is impacted by the high-temperature process stream due to temperature-dependent changes in the membrane's active layer. Temperature can also have a direct or indirect impact on viscosity, with increased water flux, reduced pressure drop, and improved external mass transfer (lower concentration polarization) as results [53].

A novel method and application for end-of-life (EOL) RO membranes are introduced in this study in response to the increasing environmental concerns regarding discarded end-of-life (EOL) membrane elements. A novel, adaptable, low-cost, and eco-friendly method is proposed in the study to repurpose end-of-life (EOL) membranes into high-performance loose NF membranes for effective dye/salt separation [56]. One of the most important applications of nanofiltration technology is removing dyes from polluted water and treating and purifying water [57].

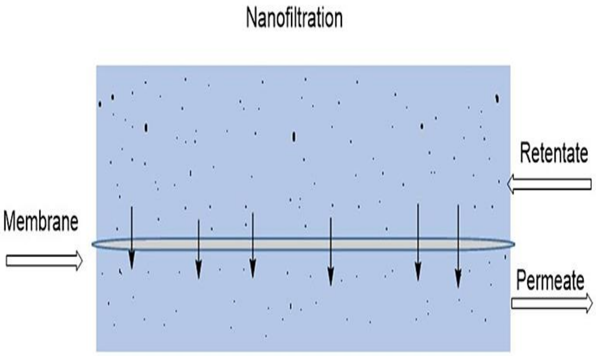

Fig. 3. A Schematic diagram illustrates nanofiltration process.

1.5. Ultrafiltration (UF)

Ultrafiltration (UF) is a type of membrane filtering in which gradients in concentration or pressure cause separation across a semipermeable membrane. Water and low molecular weight solutes can pass through the membrane in the permeate, while suspended particles and large molecular weight solutes are present in the retentate. This separation method is widely used in research and industry to concentrate and purify macromolecular (103–106 Dalton) solutions, particularly protein solutions. There is no fundamental distinction between microfiltration and ultrafiltration.

They differ from one another based on size exclusion or particle capture. It is fundamentally distinct from membrane gas separation, which separates based on varying levels of absorption and diffusion. Ultrafiltration membranes are classified using the molecular weight cut-off (MWCO) system. Ultrafiltration can be used in either a cross-flow or dead-end mode. Without the use of coagulants, dissolved material can be removed using ceramic or polymeric membranes with small poresIrena [58]. The pressure-driven membrane eliminates bacteria, viruses, end toxins, and other pathogens in addition to the majority of water turbidity [59 - 62]. One of the problems facing ultrafiltration is fouling, which was addressed by producing environmentally friendly anti-fouling membranes, which gave an acceptable result estimated at about 100% of particles larger than 10 nanometers [63]. Also, solvents were added a Deep Eutectic Solvent (DES) composed of Citric Acid (CA) and Choline Chloride (ChCl) to improve the performance of the membranes in ultrafiltration, which sufficiently enhanced the dye rejection [64].

1.6. Reverse Osmosis (RO)

Microfiltration and ultrafiltration are not fundamentally different from one another. They vary from one another according to particle capture or size exclusion. Membrane gas separation, which separates according to different degrees of absorption and diffusion, is essentially different from it. The molecular weight cut-off (MWCO) system is used for the classification of ultrafiltration membranes. There are two modes of ultrafiltration: cross-flow and dead-end. Ceramic or polymeric membranes with tiny pores can be used to remove dissolved material without the need of coagulants. In addition to removing most water turbidity, the pressure-driven membrane also gets rid of bacteria, viruses, end toxins, and other pathogens [59]. Semipermeable membranes known as reverse osmosis membranes let clean fluid flow through while rejecting contaminants from the reject stream. The majority of reverse osmosis systems use crossflow devices to shorten the time required to clean the membrane. As the fluid flows through the reverse osmosis membranes, the rejected material is eliminated downstream in concentrated rejected water (brine) [65, 66].

A schematic diagram demonstrating the RO process is shown in Figure 4. Because a pressure pump pushes fluid across a membrane, pressure is the primary force underlying the reverse osmosis process. The pressure increases in accordance with the driving factors. As a result, as the concentration of the rejected stream increases, so does the required pushing effort. Proteins, particles, viruses, salts, sugars, colors, and other things having molecular weights more than 150–250 Daltons can be rejected by reverse osmosis. Charged particles facilitate ion separation using reverse osmosis. This implies that the membrane will reject charged dissolved ions—such as organics—more frequently than uncharged ones. As the charge and particle size increase, the particle is largely rejected.

When two volumes of water (or another solvent) are separated by a semipermeable membrane, water flows from the side with the low solute concentration to the side with the high solute concentration. The flow can be stopped or reversed by applying external pressure to the side with a higher concentration. We call this phenomenon "reverse osmosis." The osmotic pressure is the pressure at which the flow stops when every solute molecule is on one side of the system. The solvent molecules that surround a "solute molecule" in a solvent significantly reduce its mobility. The mobility of the solute is entirely controlled by changes in its collisions with the molecules of the surrounding solvent. As a result, the molecules' average thermal velocity is the same as it would be if they were free to move in the gas phase. When a solute is blocked by the wall, pressure is applied to the wall, transferring momentum to it. Since the velocity is the same as that of the free molecule, the pressure on the wall will be the same as the ideal gas pressure at the same molecular concentration. The Van't Hoff equation can be used to compute osmotic pressure (π) [65-66].

$$\pi = c\,R\,T \qquad \text{Eq. (1)}$$

where c is the molar solute concentration, T is the absolute temperature, and R is the gas constant. The ideal gas pressure formula is the same as this one. RO desalination provides a broad range of capacities due to its modular design concept, ranging from big units with 395,000 m^3/day to small units with 0.1 m^3/day. Some applications for direct applications for reverse osmosis process by using modification of membrane structure. Fatima et al. We conducted a thorough mechanical evaluation of a thin-film composite (TFC) RO membrane and its individual layers under a variety of conditions, which was complemented by scanning electron microscopy. The polyester supporting layer is the primary factor in the TFC membrane's overall mechanical behavior, which is also responsible for the high anisotropic behavior [67]. other modification, This study used molecular dynamics (MD) simulations to build two nanopores with varying pore diameters and functional groups to explore water molecule directional transport. The functional groups at the margins of pores affected water flux, and graphene oxide (GO) nanopores modified by COH (hydroxyl) and CH (hydrogen) had good water permeability. For tiny pore diameters, hydrophilic GO-COH had a lower flux than hydrophobic GO-CH. At large pore diameters, the hydrophilic functional group had about 24% higher water flux than the hydrophobic group. The solid molecular affinity between water and GO-COO− surface led to a substantially larger water flux than GO-COOH. The GO-COO− hole exhibited selective water penetration [68]. Among the research that focused on developing the selective layer of reverse osmosis membranes and the accumulation of fouling on it and testing its performance, the results indicated that the intricate loading circumstances often experienced by membranes necessitate additional research to more accurately replicate actual working conditions in laboratory settings. The findings of this study enhance comprehension and forecasting of the behavior and evolution of the surface properties of the TFC layer under varying mechanical stress levels and situations.

The approaches presented herein are applicable to diverse TFC membranes utilized in several water treatment and desalination processes. This study is the inaugural investigation into the evolution of surface damage in TFC layers under varying strain limits and conditions, underscoring the necessity for further research under authentic operating environments, including acidic/basic conditions, non-uniaxial loading, and diverse temperature ranges [69].

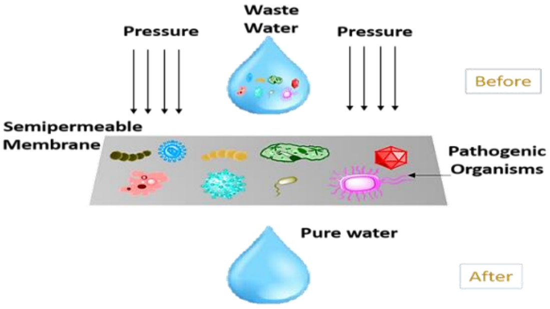

Fig. 4. Schematic diagram shows RO process

Problems faced during the operation of the RO membrane

When the membrane surface fouls while it is operating, membrane productivity is decreased, and salt rejection decreases if fouling conditions persist. Three things can cause membrane fouling: particles suspended in feed water, a buildup of minerals that are only sporadically soluble, and byproducts of microbial growth [53]. Frequent cleaning is necessary to address these situations, which is expensive and shortens the service life of the membrane elements. Generally speaking, the feed to the membranes should be free of suspended materials, and the feed needs to be properly prepared for the membrane plant to operate well. Hardness is influenced by minerals that are sparsely soluble, mainly silica and barium. Most noticeable microorgapermnism development occurs in the temperature range of 30 to 45°C [70, 71].

1.7. Forward Osmosis (FO)

The forward osmosis (FO) mechanism is depicted schematically in Figure 5. (a) The FO concept and (b) a feasible FO system with a regeneration unit for draw solutes (derived from ref. [72]. FO uses the natural osmosis process, which draws water molecules from one solution into another over a semi-permeable membrane. In this instance, a highly concentrated draw solution (DS) is utilized to create a concentration gradient to remove water molecules from the feed solution (FS). This gradient provides the osmotic pressure differential required to move water molecules from the FS to the DS. Until the chemical potential reaches equilibrium, this motion continues [73]. Except for instances where the water extracted from the feed is included into the final product, a recovery unit is always required. This device recovers fresh water and replaces the draw solution [74].

FO has numerous advantages. Because it doesn't require external pressure, the approach utilizes less energy than pressure-driven procedures, especially for specialized FO applications. Water purification and fouling reversal are made easier by the use of osmotic pressure for separation. The versatility of the draw solutions enables the simple customization of products for freshwater recovery or other applications, such as the manufacturing of beverages and pharmaceuticals. Since neither heat nor pressure is used in the latter case, the product's qualities are maintained. Costs are also reduced by reusing and regenerating DS. The demanding (highly targeted) feed solution (FS) absorbs FO more effectively. For example, FO would be a better choice because RO would need more energy to overcome the osmotic pressure in a heavily salinized meal [75 - 78].

There are certain disadvantages to consider despite all of FO's possible advantages. Aside from specific applications for draw solutions, additional separation is required to recover fresh water when the draw solute is present in the final product. Low permeating flux due to concentration polarization (CP) is another disadvantage of FO. This CP alters net osmotic pressure, which lowers permeate flux. Once again, FO's energy needs rise when the molecular weight cutoff (MWCO) falls. This is because the regeneration of draw solutes would necessitate membranes with smaller holes and higher pressures, such as RO. Consequently, the overall demand for energy increases [77, 78].

There are many applications for forward osmosis, including the removal of heavy metals from contaminated water [79] and the addition of a polyamide layer to the surface of the membranes used [80, 81]. Gamal et al. [82] proposed the creation of inorganic membranes specifically for forward osmosis to improve the performance of forward osmosis. These membranes performed well in terms of salt rejection rate, amount of water flux, and fouling on the membrane surface. The salt rejection rate was low, and the amount of water flux was high compared to similar membranes. These proposed membranes are made of inorganic materials that are environmentally friendly and harmless.

Draw the FO System's Solution Selection and Recovery

As previously stated, water molecules in FO systems are moved by concentration gradients. The draw solution (DS) provides this concentration gradient. Draw solutions are created by evenly dissolving draw agents or solutes in water. Draw solutions are crucial because they have an impact on the permeation flow and regeneration cost in FO processes [83].

There are many different drawing solutions. The following are typical draw solution properties: Their most significant feature is their high osmotic pressure. Again, DS should have low reverse solute diffusion to feed solution (FS) and be easy to refill [78]. Moreover, DS needs to be very stable, non-toxic, and very soluble in water in order to prevent precipitation [84]. In general, there are many different types of draw solutes: organic (sucrose, glucose, fructose, EDTA, sodium polyacrylate, sodium lignin sulfonate (NaLS), etc.); inorganic (NaCl, $MgCl_2$, Na_2SO_4, KCl, KNO_3, etc.); magnetite nanoparticles (Fe_2O_4); gases; and volatile chemicals (ammonia and CO”) [85, 86].

The type of draw solute recovery method chosen depends on the draw solute's characteristics. For salt-based draw solute recovery, membrane separation techniques including UF, MD, RO, and NF are employed. Thermal separation of NH_3/CO_2 is utilized for gases and volatile chemicals like SO_2. Sulfate based draw solutes such as $Al_2(SO_4)_3$, $Mg(SO_4)$, and $Cu(SO_4)$ can be precipitated using alternative methods, and hydrogels and magnetite nanoparticles can be recovered using a stimuli-based procedure [87, 88]. Comparison of different membranes regarding pore size and applied pressure is given in Table 2.

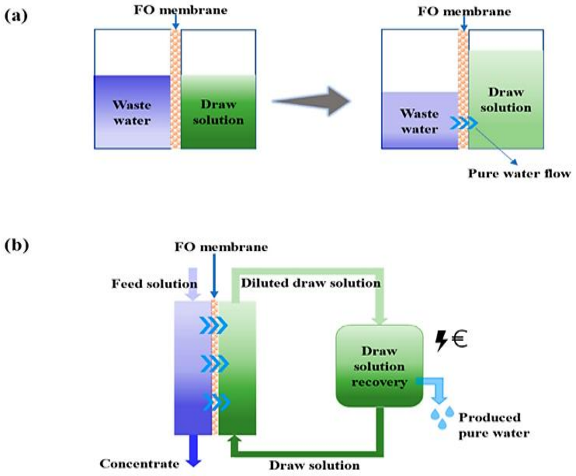

Fig. 5. The schematic diagram illustrates the FO process. (a) FO concept and (b) a workable FO system with a draw solutes regeneration unit [72].

Table 2: Comparison of Membranes Applied for Different Desalination Processes

Process	Pore Size	Driving Force	Transport Mechanism	**Ref.**
Microfiltration	0.05-10 µm	1-2 bar	Sieving	**[89]**
Ultrafiltration	0.001-0.05 µm	2-5 bar	Sieving	**[90]**
Nanofiltration	< 2.0 nm	5-40 bar	Capillary Flow	**[91]**
Reverse Osmosis	< 1.0 nm	40-100 bar	Capillary Flow	**[92]**

2. Pretreatment Strategies for Membrane Processes

Prior to using membrane separation techniques, wastewater must first undergo pretreatment. The efficiency of the membrane process depends on the feeding before treatment. Pretreatments improve energy efficiency while reducing membrane fouling. In theory, the first treatment modifies wastewater's physical, chemical, or biological characteristics to improve membrane separation [93]. In order to prepare influents for membrane separation, a variety of techniques are employed as preliminary treatments. Several times, wastewater has been pretreated using physicochemical processes like coagulation, adsorption, and softening prior to membrane separation [94]. In the process of purifying generated water, Sardari et al. [95]. Before receiving treatment for DCMD, electrocoagulation was employed. The recovery of water from generated water with 135 /L dissolved solids was 57%, according to the data.

In comparable uses, Chang et al. [96] and Kong, et. Al [97]. Before receiving UF treatment, the generated water and natural gas flow back water underwent chemical coagulation as part of the preliminary treatment. The ability to sustain a steady flow and a notable reduction in membrane fouling were shown in both tests. These physicochemical pretreatment methods are an efficient way to get rid of organic pollutants that have a high tendency to foul membranes and suspended particles. Adsorption and coagulation/flocculation can also be combined as membrane process pretreatment techniques. This will improve the wastewater's capacity to eliminate colloidal and dissolved particles, as shown by [98 - 100].

Another method for pretreatment of membrane processes is pre-filtration. With low BOD and turbidity levels and undetectable levels of both total and fecal coliform bacteria, the resultant effluent was judged to be of good quality. In a comparable application, López Zavala, et. Al [101] Gray water from washing machine outputs was pretreated using felt and compressed polyester. By enhancing flow and lowering fouling rates, the pretreatment process was proven to enhance MF and UF performance. Once more, in the filtration of wastewater from the olive mill in Peloponnesus, Greece, Paraskeva, et. [102] investigated the mixture of UF and RO. Before the wastewater was treated with UF, suspended particles were removed using an 80 µ polypropylene filter. The resulting wastewater was suitable for disposal and irrigation. Dissolved air flotation is one of the additional preparatory techniques [103] and biological initial treatment Methods [104].

3. Concentration Polarization and Membrane Fouling

3.1. Concentration Polarization (CP)

Particle concentrations close to the membrane surface are higher than those in the fluid's bulk, a phenomenon known as CP [105]. The phenomenon known as CP can occur during any membrane filtering process. When solute particles flow through a membrane, CP creates a layer of gathered particles on the membrane surface. There is a notable difference in particle concentrations between the membrane's feed and permeate sides since the permeate has a lower particle concentration [106]. Such a concentration differential would cause the solvent molecules to migrate backward until equilibrium was achieved. CP develops in the porous support layer of FO. This is known as internal concentration polarization (ICP). CP affects permeate flux because the boundary layer formed by the buildup of solute particles makes it difficult for permeate to flow through the membrane. This reduces the longevity of the membrane. This ultimately leads to high membrane process costs.

Pretreatments, membrane modification, fluid management, and thorough cleaning are common methods for reducing CP [107, 108]. Pretreatment eliminates or reduces the particles that lead to concentration polarization. Internal concentration polarization in FO membranes is primarily addressed via membrane modification. Wang et. Al [109] fashioned cellulose acetate (CA) into a double-skinned FO membrane and found that it showed great promise for reducing ICP. Once more, Chi et al. [110] utilized the interaction between magnetite and magnetic draw solutions; magnetite nanomaterial was used to replace the surface of the cellulose triacetate FO membrane (CTA) in order to reduce ICP. It was demonstrated that the novel method successfully reduced ICP in the FO membrane. In a similar vein, Liu et. al [111]. used the extremely hydrophobic polyether sulfone coated in $CaCO_3$ to modify the surface of a thin film composite (TFC) FO membrane. This blocked ICP and improved the membrane's natural ability to draw water.

In pressure-driven membrane processes, flow dynamics—such as turbulent flow regimes, flow in curved channels, membrane module vibrations, and pulsative flow techniques—are frequently used to control capillary pressure [107]. Mo et. Al [112] investigated how adding spacers to a membrane channel affected CP. The study found that spacers can provide hydrodynamic conditions that reduce CP. Bhattacharjee et. al [113] Spiral components, cylindrical rods, thin wires, spacers, static mixers, and kinetics mixers are frequently employed to generate turbulence in membrane filtration systems in order to enhance permeate flow and regulate CP, according to a review of permanent turbulence supporters in cross-flow filtration. Su et al.'s study [114] used motions to control CP in the RO membrane module during desalination. The method helped reduce CP while also improving membrane flow. CP reduction can also be facilitated by routine cleaning techniques. Backwashing, backflushing, chemical cleaning, and hand cleaning are some of these techniques. Boundaries layer film theory can be used to define concentration polarization on the FS side in the active layer-feed solution (AL-FS) direction for the FO system [115].

$$C_m - C_p \big/ C_b - C_p = e^{Jw/Ktot} \qquad \textbf{(Eq. 2)}$$

Where the concentrations of volume feed solution, membrane interface, and permeate water are indicated by the symbols C_b (mg L^{-1}), C_m (mg L^{-1}), and C_p (mg L^{-1}).

$K_{tot:}$ is the coefficient of total mass transfer (L/(m^2 h)), this is determined by dividing the salt diffusion coefficient D_s by the boundary layer thickness δ, or $K_{tot} = D_{draw}/\delta$.

As shown in Fig. 6, the mass transfer coefficient fell, and the water concentration at the membrane interface (Cm) was lower at the end stage than it was at the start. This is because the development of a fouling layer on the surface of the FO membrane hinders the convection mechanism more than the diffusion mechanism. Consequently, the concentration on the membrane surface was lower {Fig. 6 (b)} than would be expected for a normal concentration polarization caused by convection and diffusion {Fig. 6 (a)}. In seawater reverse osmosis (SWRO) operations, this phenomenon has been documented as cake-reduced concentration polarization (CRCP) [116]. When contrasted with the usual concentration polarization brought on by convection and diffusion, the rejection rate is improved. In a similar vein, CRCP might improve flux efficiency. But compared to cake-enhanced concentration polarization's (CECP) detrimental effects on water flows, CRCP's beneficial effect is far less significant [117]. Therefore, in assessing flow behaviors, CRCP is insignificant. To summarize, the water permeability was decreased due to the fouling layer that was created on the FO membrane's active layer (AL), as depicted in Figure 6. Additionally, the fouling layer's low selectivity meant that it had less of an effect on solute fluxes than on water fluxes, which over time led to an increase in Js/Jw.

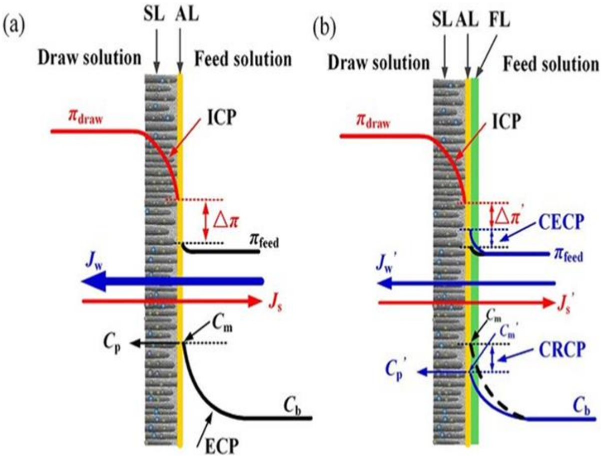

Fig. 6. (a) FO membrane in its initial state; (b) FO membrane with fouling layer [118]

Note that the active layer is AL, the fouling layer is FL, and the support layer is SL. External concentration polarization is known as ECP, and internal concentration polarization is known as ICP. Cake-reduced concentration polarization is known as CRCP, and cake-enhanced concentration polarization is known as CECP.

3.2. Membrane fouling

When bacteria, organic pollutants, and suspended particles build up on the membrane's surface or in its pores, a condition known as membrane fouling occurs, which lowers the permeate flow [119]. Fouling is thought to be irreversible when materials called foulants are deposited inside a membrane's pores. A cake layer that prevents flow penetration is created by simple foulant deposits on the membrane's surface. It is believed that the fouling can be reversed [120].

Membrane fouling severely hinders permeate transfer, which reduces the membrane's performance. Therefore, higher pressure than normal is needed to ensure that permeate flows through the membrane. The more fouling there is, the more pressure is needed. Membrane fouling negatively impacts membrane performance by significantly reducing permeate mobility. Therefore, more pressure than usual is required to ensure that the penetration passes through the membrane. As fouling accumulates, more pressure is required [120,121]. Membrane fouling has a detrimental effect on the membrane's overall performance. They include reduced membrane filtering areas, more energy usage, longer downtime, and so on. There are various types of fouling, depending on the foulant. These include colloidal fouling, organic fouling, biofouling, and inorganic fouling (scaling) [122]. Colloids can be mixed, organic, or inorganic. These could include bacteria, biological detritus, clay, silt, polysaccharides, lipoproteins, lipids, iron and manganese oxides, and more. These compounds build up and adhere to the membrane material over time [123].

"Biofouling" refers to the formation and expansion of biofilms on a membrane. Most of these biofilms are composed of microbial cells and extracellular polymeric substances (EPS), which are produced when bacteria stick to wet surfaces. By sealing the holes in the membrane and increasing barrier to permeate passage, these organisms develop and consume the nutrients that have accumulated in the system in this medium [124].

The accumulation of inorganic salts on the membrane surface is known as inorganic fouling (scale). $CaSO_4$, $CaCO_3$, and SiO_2 are examples of these salts, but they are not the only ones [125]. Scales occur on the membrane surface when concentrations of salts that are poorly soluble above their limits of solubility [126]. Organic fouling occurs when naturally occurring organic materials' organic compounds adsorb on the membrane's surface and build up over time, preventing permeate passage over the membrane [122]. Remember that membrane fouling is influenced by feed properties such as pH and ionic strength, membrane properties such as roughness and hydrophobicity, and process variables such as temperature, trans-membrane pressure, and crossflow velocity. These elements all contribute to membrane fouling in one way or another [127 – 129].

3.2.1. Methods of Fouling Control (Membrane Cleaning)

Size exclusion is the main goal of membrane separation. The membrane eventually becomes contaminated by the rejected particles. Therefore, fouling in the members is unavoidable. Many strategies have been proposed to reduce membrane fouling. The importance of these processes is determined by the properties of the membrane and feed solution. External fields, turbulence inducers, membrane material modifications, and boundary layer velocity control are some of these strategies [130]. Williams and Wakeman [131] encouraged flow control, feed pretreatment, membrane rotation, and gas sparging. Cleaning a membrane increases its permeation flux, which has been decreased by fouling. This entails removing deposited materials to allow permeate to pass through the membrane. Membrane cleaning can be broadly categorized as physical, chemical, biological/biochemical, or physic-chemical. While the membrane module is removed and cleaned separately, it is referred to as ex-situ cleaning; while it remains inside the reactor during cleaning, it is referred to as in-situ cleaning [132,133]. Fig. 7 shows a schematic diagram illustrating membrane cleaning.

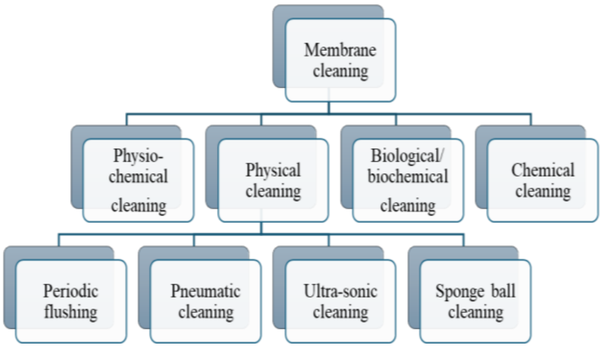

Fig. 7. A schematic diagram illustrates membrane cleaning methods

3.2.1.1. Physical cleaning

Foulants are extracted and displaced from the membrane using mechanical treatment [134]. These treatments involved:

A. Periodic back flushing

In order to induce the permeated to move through the membrane in the other direction, pressure must be applied to the permeated side of the membrane. This causes the deposited materials to be lifted from the membrane surface. To create the backwash, a pressure higher than the filtration pressure is needed [128].

Backwashing is the fouling reversal technique most used in industry. It is possible to successfully recover fouling that results from material deposition on membrane surfaces as a gel or cake layer. However, this approach makes it challenging to eliminate irreversible fouling, which is mostly brought on by contaminants that have dissolved and obstructed the membrane pores [135].

B. *Pneumatic cleaning*

This covers air sparging, scouring, and lifting. This involves cleaning the membrane with air under pressure. The air destabilizes and loosens the foulants by exerting a shear strain on the membrane surface. Air can be utilized for direct cleaning or to bubble through the feed to improve permeate flow. This procedure is advantageous because it doesn't use chemicals, but the expense of pumping air is a crucial factor to take into account [136].

C. *Ultrasonic cleaning*

This method uses ultrasonic waves to stir a liquid medium. The process of cavitation involves the formation, growth, and rupture of bubbles, which transfer energy to the membrane surface in the form of turbulence that pushes foulants out [137]. Because the vibrations are conveyed at the molecular level, ultrasonic cleaning effectively cleans the membrane's surface. The physical cleaning process is influenced by crossflow velocity, cleaning temperature, pulse length, and ultrasonic power [138].

D. *Sponge ball cleaning*

Sponge balls are used to clean membrane surfaces. By scraping off the foulants as it goes through, the sponge ball—typically composed of polyurethane—cleans the membrane's surface inside the permeator. Tubular membranes with extraordinarily large diameters can be cleaned mechanically using this method [139].

3.2.1.2. Chemical cleaning

When fouling is irreversible, it can be used. Chemical cleaning is based on an understanding of how foulant and membrane material, foulant and cleaning chemical, and cleaning chemical and membrane material interact. These are essential for choosing the right chemical for the cleaning process [140]. Cleaning is expected to remove and dissolve foulant while maintaining it in solution and halting more fouling without causing any harm to the membrane being cleaned. Chemical cleaning is typically accomplished by filling the retentate channel with a cleaning solution (detergent), which progressively weakens the foulant's bindings. This process is known as cleaning in situ (CIP). This enables frequent crossflow to eliminate these contaminants [141]. Acids, alkalis/bases, chelating agents/sequestrates, enzymes, surfactants, and disinfectants are the different categories of cleaning agents. These agents are all used to get rid of foulants with different charges or compositions. For instance, acid cleaning is intended to get rid of metal oxides and inorganic foulants like salt scales or precipitates. Frequently utilized acids include phosphoric acid (H_3PO_4), nitric acid (HNO_3), sulfuric acid (H_2SO_4), and hydrochloric acid (HCl) [142]. Alkalis and bases are typically used at high pH levels (11–12) or lower, depending on the kind of membrane. Cleaning organic fouling is their main application. The most commonly used alkali or base is sodium hydroxide (NaOH). Two further types of alkalis that are used are phosphates and carbonates [134].

Chemically irreversible fouling (CIF) and erosion resulting from chemical cleaning of ion-exchange membranes (IEMs) lead to alterations in desalination performance and membrane characteristics, a phenomenon referred to as membrane aging [143]. Chemical erosion resulted in the deterioration of functional groups and the polymer matrix, as seen by alterations in ion exchange capacity, contact angle, thermal stability, and mechanical strength. The disposal of end-of-life membranes in landfills presents considerable financial and environmental issues, requiring sustainable management solutions. An innovative and robust method is proposed to recycle end-of-life membranes and customize their surface properties for various applications. Chemical cleaning and surface modification employing a polydopamine (PDA)-inspired coating were utilized for membrane recycling. A unique functional surface layer was developed, exhibiting performance akin to that of conventional wastewater treatment membranes, as evidenced by thorough chemical and morphological surface characterization [144]. It gives valuable results that are comparable to previous similar works.

3.2.1.3. Biological/biochemical cleaning

It is the process of removing contaminants from membranes with the use of bioactive substances like signal molecules, enzymes, or enzyme combinations [145]. The membrane is deteriorated by physical and chemical cleaning; biochemical and biological approaches are more environmentally friendly and sustainable. Quorum quenching, energy uncoupling, and enzymatic cleaning are frequently used as cleaning methods, especially in membrane bioreactors [146]. This type of cleaning is most commonly utilized to clean the membranes used in abattoir wastewater treatment processes.

3.2.1.4. Physico-chemical cleaning

This method eliminates foulants by combining physical and chemical cleaning, as the name implies. Chemical compounds are used to improve the effectiveness of physical cleaning techniques. Chemically enhanced backwashing (CEB) is a common physicochemical cleaning method. Another example is the use of ultrasonic cleaning in chemical cleaning, which can boost flow recovery by up to 95% [147, 148].

Summary

Water covers three-quarters of the Earth's surface. Since freshwater only accounts for 1% of the planet's total water supply, it is challenging to assert that all of this water is fresh or fit for human consumption.

Fresh water is desperately needed in the majority of nations worldwide. As a result, numerous water treatment technologies have been created and enhanced. Every year, there are more water desalination plants. One of the most significant water treatment methods is the desalination of salt water, particularly when membranes are used. Membranes are thought to be the secret ingredient for purifying and separating various liquors. Water desalination, wastewater treatment, gas separation, dialysis, and the food and beverage sectors are just a few of the industrial uses for membrane-based water treatment technology.

Membrane types are reviewed. Additionally, a comparison of inorganic and organic membranes is provided. Additionally, this review article provides a detailed explanation and discussion of membrane-based water desalination techniques. This covers reverse osmosis, forward osmosis, membrane distillation, pervaporation, electrodialysis, and electrodialysis reversal, among other processes. Additionally, a thorough analysis and discussion of membrane fouling techniques and the procedures used to control (clean) fouling are provided. Periodic back flushing, pneumatic cleaning, ultrasonic cleaning, sponge ball cleaning, chemical cleaning, biological/biochemical cleaning, and physico-chemical cleaning are examples of physical cleaning methods.

Because of their superior qualities—such as their extended lifespan, excellent chemical resistance, good mechanical and thermal stability, and autoclavability—inorganic membranes are often better suited for usage in challenging settings like corrosive and hot ones. However, hazardous solvents are not used in the production of inorganic membranes. Inorganic membranes are still not widely marketed, and their cost remains high.

By doping with nanomaterials like graphene oxide, inorganic membranes can be created.

Future research should focus on the following areas:

- Creating a commercial membrane that significantly reduces concentration polarization and membrane fouling.
- Investigating enhanced drawdown solutions and energy-efficient recovery methods to facilitate the regeneration of drawdown solutions.
- Implementing demonstration projects or pilot plant-scale experiments is essential to promoting commercial water treatment technology uses.
- Expanding potential industrial application areas is critical to developing commercial markets for all water treatment processes.
- Improving the utilization of water and wastewater treatment technology, increasing recovery efficiency, and reducing energy consumption in energy-intensive processes.

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