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Review

Synthetic composite membranes and their manifold applications: A comprehensive review

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Abstract: Synthetic membranes play a crucial role in a wide range of separation processes, including dialysis, electrodialysis, ultrafiltration, and pervaporation, with growing interest in synthetic emulsion membranes due to their precision, versatility, and ion exchange capabilities. These membranes enable tailored solutions for specific applications, such as water and gas separation, wastewater treatment, and chemical purification, by leveraging their multi-layered structures and customizable properties. Emulsion membrane technology, particularly in pressure-driven methods like reverse osmosis (RO) and nanofiltration (NF), has shown great potential in overcoming traditional challenges, such as fouling and energy inefficiency, by improving filtration efficiency and selectivity. This review explores the latest advancements in emulsion membrane development, their adaptability to various industrial needs, and their contribution to addressing long-standing limitations in membrane separation technologies. The findings underscore the promise of emulsion membranes in advancing industrial processes and highlight their potential for broader applications in water treatment, environmental management, and other key sectors.

Keywords: synthetic composite membranes; membrane stability; emulsion membrane manufacturing; water and wastewater treatment; medicinal and medical operations; membrane filtering technology

1. Introduction

Membrane technology is very important to medical operations, especially for several life-saving treatment modalities. Membranes are employed in bio separations, individual bias, tissue regeneration, artificial organs, medicine distribution, and coatings for medical bias [1]. The total membrane area generated during medical procedures is almost equal to the entire area of all artificial membrane procedures combined. Medical membrane products actually have a significantly higher financial value than all of the other combined operations [2]. For example, the medical membrane request grows rapidly and exceeds 1.5 billion bones per time only in the US. The majority of medical requests concern membranes used in tissue engineering, hem dialysate, artificial organs (pancreas, oxygenators, etc.), and medicine distribution [3,4]. This review will go into great detail on these topics. For the production of the membranes, biocompatible and, in certain situations, biodegradable accessories are required. Therefore, we compactly bind the biocompatibility and biodegradability difficulties prior to the specified operations [5].

Medical implants have well-defined and controlled interfaces, as biomedical engineers have realised recently. A significant hindrance to the clinical implementation of active bias devices carrying out physiologically beneficial tasks has been the decline in function upon implantation as a result of inadequate comprehension of the implantation interface [6]. Even in cases where a medical implant device exhibits satisfactory in vitro performance for extended periods of time, long-term in vivo functionality is still unattainable. Due to its ability to be formed from a variety of materials and having multiple layers, composite membranes have garnered a lot of attention [7]. This will make it possible for researchers and businesses to create customised membranes for certain uses. Because of their synthesis's flexibility, composite membranes can be employed in a variety of advantageous methods for both liquid and gaseous applications. Nowadays, most commercial membranes are made of thin composite materials, such those used in reverse osmosis and nanofiltration [8,9].

Developing energy storage systems that are efficient and reliable is crucial for the global effort to transition away from conventional energy sources. In addition to bacterial batteries, hybrid batteries, and hybrid redox flow cells, new electrochemical energy storage technologies are on the horizon. As an alternative to traditional electrochemical cells, these alternative architectures offer a high degree of energy conversion efficiency. They are also highly modular in terms of the design of devices and flexible in terms of material and operating conditions [10]. These various gadgets have power outputs ranging from several megawatts to a few milliwatts. Now that solid-state batteries with extended cycling capabilities and high energy density are available, sustainable electronic devices and point-of-care equipment can be manufactured. In recent years, lithium-ion batteries have approached the capacity of new batteries utilizing earth-abundant metal ions [11].

2. Major classification of composite membrane

Composite membranes are classified into major categories based on their composition, structure, and functional design. The following are the major classifications of composite membranes:

2.1. Polymeric composite membranes

These membranes are composed of two or more polymeric materials that are combined to create a membrane with enhanced performance characteristics. By blending polymers, the resulting membrane benefits from the desirable properties of each polymer, such as flexibility, mechanical strength, and chemical resistance. Polymeric composite membranes are typically used in applications like microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF). Examples include blending materials like polyvinylidene fluoride (PVDF) with other polymers to improve hydrophilicity and fouling resistance in water treatment processes [12].

2.2. Inorganic composite membranes

Inorganic composite membranes are made from materials like ceramics, metals, or carbon-based materials. These membranes are known for their thermal stability, chemical resistance, and mechanical strength, making them suitable for extreme conditions such as high temperatures, aggressive chemical environments, and high-pressure systems [13]. Ceramic composite membranes, for example, are commonly used in industrial processes like gas separation, catalytic reactions, and water treatment due to their durability and resistance to fouling. They can also handle harsh solvents, making them valuable in chemical and pharmaceutical industries [14].

2.3. Polymer-inorganic hybrid membranes

These membranes combine organic polymers with inorganic materials, such as metal oxide nanoparticles (e.g., zinc oxide or titanium dioxide) or carbon nanotubes, to create hybrid structures that merge the flexibility and ease of fabrication of polymers with the robustness and high separation performance of inorganic materials [15]. Polymer-inorganic hybrid membranes are engineered to enhance properties like selectivity, mechanical stability, and fouling resistance. These hybrid membranes are often used in advanced water treatment processes, gas separation, and membrane distillation, where high performance is needed under challenging operating conditions [15].

2.4. Thin-film composite (TFC) membranes

Thin-film composite membranes are widely used in pressure-driven membrane processes like reverse osmosis (RO), nanofiltration (NF), and forward osmosis (FO). TFC membranes consist of a thin selective layer, often made of a polymer such as polyamide, that is cast onto a porous support substrate [16]. The thin selective layer governs the separation properties, while the porous support provides mechanical strength. TFC membranes are prized for their high permeability and selectivity, which makes them highly effective in applications like desalination, wastewater treatment, and brine concentration. The thin selective layer can be further modified to enhance specific separation characteristics, such as salt rejection or pollutant removal [17].

2.5. Mixed-matrix membranes (MMMs)

Mixed-matrix membranes are composite membranes where inorganic fillers, such as zeolites, metal-organic frameworks (MOFs), silica, or carbon nanotubes, are dispersed within a polymer matrix [18]. The incorporation of these fillers enhances the membrane’s separation capabilities by improving selectivity, permeability, and resistance to physical degradation. MMMs are designed to combine the advantages of both inorganic and organic components, offering higher performance than pure polymeric membranes. They are particularly useful in gas separation applications, such as carbon dioxide capture, natural gas processing, and the separation of organic solvents. By fine-tuning the dispersion and interaction between the fillers and the polymer matrix, MMMs can be optimized for specific separations and challenging environments [19].

3. Characteristics of composite membranes

Composite membranes are characterized by enhanced selectivity and high permeability, allowing for efficient separation of specific particles or molecules in various applications [20]. Their multi-layered structure, typically featuring a thin selective layer atop a robust support, provides excellent mechanical strength and thermal and chemical stability, making them suitable for high-pressure and harsh industrial environments [21]. Many composite membranes exhibit improved fouling resistance through the incorporation of hydrophilic materials or nanoparticles, extending their operational lifespan and reducing maintenance needs [22]. Customizability is a key feature, enabling tailored properties to meet specific application requirements, which, coupled with their scalability, makes them ideal for large-scale processes like water treatment and gas separation. Additionally, composite membranes contribute to energy efficiency by reducing hydraulic resistance and optimizing performance, further enhancing their value across diverse industries such as pharmaceuticals, food processing, and environmental management [23].

4. Composite membrane and their applications

Generally, synthetic membranes are used in laboratory separations for separation purposes since they are synthetically created. The use of synthetic membranes in artificial processes has been successful for a long time now, on a small and large scale [24,25]. Synthetic membranes can be found in a wide variety. Most synthetic membranes in the laboratory are composed of polymeric structures, but they can also be made from inorganic materials such as liquids or polymers [26]. On the basis of the chemistry of the face, the bulk structure, the morphology, and the product system, they can be classified. Synthetic membranes and patches are chemically and physically characterized by their physical parcels, as well as the driving force that determines how they are separated [27]. An in-vitro membrane process is primarily driven by pressure and grade of attention. The separate membrane process is thus known as filtration. It is possible to utilize synthetic membranes with different figures and inflow configurations in a separation process [28]. As well as disseminating and governing them, they can also be grouped based on their operations and separations. In addition to water sanctification, reverse osmosis, dehydrogenation of natural gas, microfiltration and ultrafiltration, and junking of microorganisms from dairy products, dialysis also uses synthetic membranes to separate matter [29]. Following is a list of some of the most important applications of membrane processes **Figure 1**.

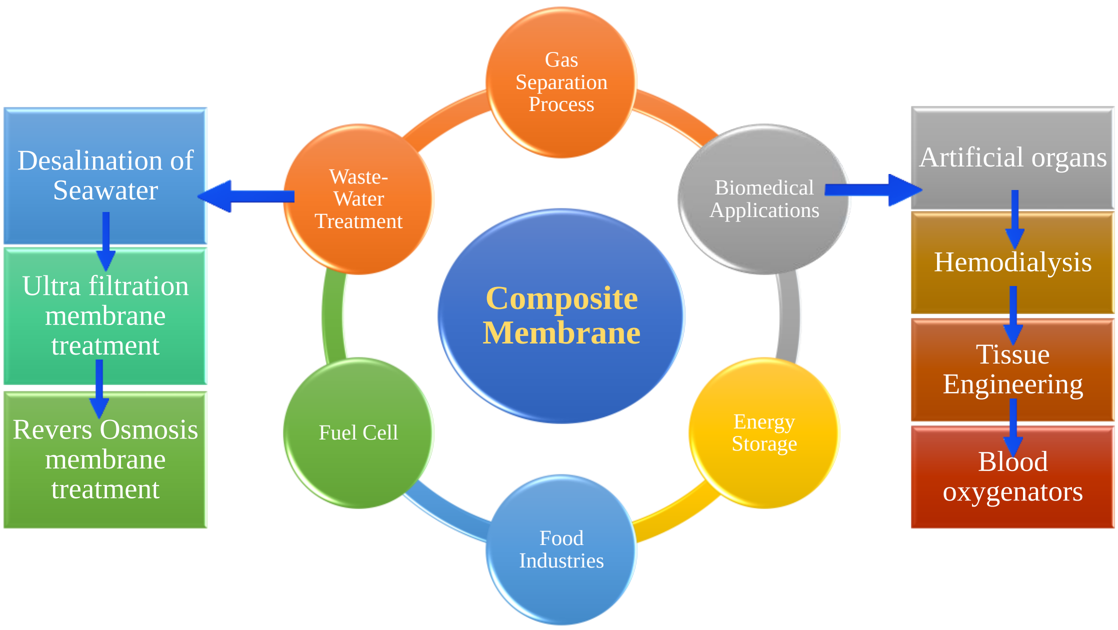

Figure 1. Flow chart of various important composite membrane applications.

4.1. Composite membrane in water treatment

Membrane technology has emerged as a crucial solution for addressing the global water crisis by purifying seawater and treating wastewater. This technology leverages various types of membranes, including reverse osmosis (RO), ultrafiltration (UF), nanofiltration (NF), and microfiltration (MF), each tailored for specific applications based on their unique properties. RO utilizes a semi-permeable membrane that effectively separates dissolved salts and organic molecules, making it widely used in desalination and producing high-purity water, despite its challenges of high energy consumption and membrane fouling. UF membranes, with larger pore sizes, are effective in removing larger particles, colloids, and bacteria, often serving as a pre-treatment step for RO systems and in wastewater treatment, while also facing issues related to organic fouling. NF membranes bridge the gap between UF and RO by selectively allowing the passage of divalent ions and organic molecules, making them suitable for water softening and polishing processes, though they can also suffer from fouling and limitations in monovalent ion rejection. MF membranes, the largest in pore size, are effective in removing large particles and microorganisms from water, commonly used in water treatment and beverage clarification, but they are limited in their ability to remove dissolved substances. A significant drawback of membrane technology is membrane fouling, caused by the accumulation of particles, colloids, and microorganisms that impede water flow, categorized into organic, inorganic, and biofouling. To mitigate fouling, strategies such as pre-treatment, membrane surface modification, and regular cleaning are employed. Despite advancements in material science and membrane chemistry enhancing performance, ongoing research focuses on developing innovative membrane structures and materials, optimizing device designs to improve flow dynamics, and reducing costs to make membrane technology more accessible. By enhancing the efficiency and performance of composite membranes while addressing existing challenges, membrane technology is positioned to play a pivotal role in sustainable water management, crucial for meeting the growing demand for clean water in a world increasingly facing water scarcity. The treatment of water is divided into several subcategories:

4.1.1. Waste-water treatment

The treatment of wastewater is one of the most important applications for membranes. In the early stages of its manufacture, ultra-modern UF was used to treat sewage and wastewater in order to remove particulate matter and macromolecular constituents [30]. There have been many applications developed for this technology, including water treatment and replicas handling as well as biotechnology and food processing. There are many methods for treating conventional wastewater, including chemical addition (aluminium sulphate, polymers, and lime), coagulation, and flocculation [31]. Sedimentation, filtration, and chlorine- grounded disinfection unfortunately; chlorine must be removed if chlorine-sensitive RO or NF is performed latterly. Trihalomethane (THM) and synthetic organic chemicals may also need to be removed in agreement with fresh regulations. In relevance of micro-organisms that could be dangerous to one's health, MF (Microfiltration) and UP are especially helpful [32]. The conformation of microfilms on the membrane's percolate side is one implicit issue. Strong boluses of chlorine, a detergent, can be used to treat this reverse flushable membrane systems (concave filaments) pottery. In the long run, UF membranes may be superior to MF membranes because they are more at removing contagious. These membranes generally last for about five times. Devilish hardness might bear water mellowing, which should likewise be possible by NF. In order to ensure a long reverse osmosis membrane life, pre-treatment is required, but it is costly and accounts for one third of operating costs [33].

In recent decades, environmental concerns about the wide application of petroleum-based synthetic polymers have pushed naturally occurring polymers to gain prominence [34]. In medicine delivery systems, tissue engineering, membrane technology, biosensor bias, etc., bio-based polymers are constantly gaining new disciplines of application in biocompatible and environmentally friendly ways. In order to fabricate fully or semi-biodegradable wastewater treatment membranes, scientists are applying colourful kinds of biopolymers, like cellulose, chitin, bounce, and alginate [35]. Biopolymers, in addition to being biocompatible, possess a number of desirable characteristics, like hydrophilicity and functionality, that make them ideal candidates for improving the effectiveness of compound membranes in purifying water. The introduction of organic and inorganic complements is also a key focus in elevating the thermo-mechanical and chemical stability of these bio-based accoutrements.

The following issues are addressed in this review:

1) The potential use of biopolymers as raw materials for the synthesis of water treatment membranes is explored here.
2) The structural characteristics of these membranes are considered in developing a comprehensive categorization.
3) Examining the effectiveness of these membranes at barring various types of pollutants from backwaters, as well as their strengths and weaknesses.

4.1.2. Desalination of seawater or brackish water

About half of the presently installed reverse osmosis systems desalinate seawater or brackish water. The salt content of harsh water is higher than that of new water, but lower than that of ocean water [36]. In fact, bitter water contains somewhere in the range of 0.5 and 30 grams of salt for every liter or 0.5 to 30 sections for each thousand, the near expenses of the significant desalination advances are as an element of salt focus. Desalination can also be accomplished using competing techniques like ion exchange, electro-dialysis, and multi-effect evaporation. In any case, the utilization of these three techniques relies upon the degree of salt fixation. 500 mg/L is the concentration that the World Health Organization (WHO) recommends for salt in drinking water [37]. Thus frequently 90% of salt in bitter water must be eliminated. Reverse osmosis's first application was a membrane made of cellulose acetate, which is easy to make and meets this requirement [38]. Seawater has a salt centralization of 3.2%–4.0% and membrane with higher salt dismissals is wanted. Cellulose acetic acid derivation films accomplish a salt dismissal of 97 close to 100% which was somewhat beneath the ideal level. Poly amide empty fine strands and inter facial composites then evolved to meet the ideal necessity [39].

Technologies of desalination and water exercise have been developed rapidly over the past few decades throughout the world to provide safe, clean water to address these grand challenges [40]. Water pollution has become a major concern as we strive to supply affordable and safe drinking water. Water treatment has emerged as a promising solution to overcome water pollution and to meet the ever-growing demand for water. A wide range of membrane and non-membrane approaches to water treatment styles have been developed over the past decades as a result of technological advances in material engineering. For example, adsorption, multistep coagulation, flocculation, ozone treatment, rush, sedimentation, and filtration have been developed. The process of desalinating water involves removing salty water and producing fresh water by removing swabs of it. There is a wide variation in the description of fresh water depending on the country [41]. Two methods of desalination are available: thermal (multi-stage flash) and membrane (RO). According to the US Environmental Protection Agency, water for fresh purposes should contain no more than 250 milligrams per liter of chloride and 500 milligrams per liter of total dissolved solids (TDS) [42].

Thermal (multi-stage flash), this type of technology is used to evaporate water and generate steam, which is then used to power turbines to generate electricity. It is an efficient and cost-effective method for producing electricity [43]. Reverse osmosis (RO) is a process in which water is forced through a membrane under pressure, leaving behind impurities. It is an effective method for purifying water and removing contaminants. Reverse osmosis is a common method for treating drinking water [44].

4.1.3. Reverse osmosis membrane treatment process

The process of osmosis describes the passing of a detergent (generally water) through a semi-permeable hedge from one side with lower solute attention to the other side with higher solute attention. Water inflow continues until chemical implicit equilibrium of the detergent is achieved. Since RO membranes are able to perform the RO processes efficiently, they are of great interest because they consume little energy, require a small space, and emit little carbon dioxide when they are used [45]. A further benefit of RO membranes is that they are non-porous and, thus, they are capable of blocking patches, ions, and organic substances. As with total dissolved solids (TDS), RO membranes can reject 90–99 percent of pollutants. Depending on the size and charge of the charge, as well as the relationship between solute, detergent, and membrane, their rejection performance will vary. It is also important to consider operating conditions and membrane parcels as well as the quality of the feed water in order to increase the efficiency of this process [46].

The bibulous pressure represents the difference in pressure between the two sides of a membrane at equilibrium [47]. In the present invention, the goal is to provide a rear osmosis compound membrane that is highly swab rejection resistant, highly water permeable, and fouling tolerant, which can be used in practical desalination at a low pressure, as well as a reverse osmosis treatment system for water provides a reverse osmosis compound membrane comprising a spongy sub caste, and a separation sub caste (also appertained to as a skin sub caste) formed on a face of the spongy sub caste, At least one substance belonging to the group consisting of electrically neutral organic substances and electrically neutral polymers is present in the separation sub caste, or at least one substance belonging to the group consisting of electrically neutral organic substances and electrically neutral polymers is carpeted over one of the faces of the separation sub caste. The subcaste or the separation subcaste before the face coating contains a limited range of specific face areas with at least one substance present.

It was investigated whether HT (high temperature) objectification and the use of 3-3-(trimethoxy silyl) propyl ammonium chloride (DMOTPAC) called the (VENUS-5700) graft enhanced membrane selectivity [48]. It was measured how much water was flowing through a swab and how much was rejected. It is believed that HT objectification improved the water flux of RO membranes, which may have been due to the increase of the face roughness, the improvement of hydrophilicity, and the construction of water channels [49]. The incorporation of HT led to significant face roughness, thus allowing water to flow more freely, since a smaller area was available for filtration. As a result of the hydrophilic surface of Dad-HT-0, it had a greater ability to relate to water and improved the flow of water. As a result of the pores in the HT matrix and the gaps between the nanoparticles and the matrix of PA, water could move at a high speed, thereby increasing the flow of water. A gradual decrease in the water flux was observed after DMOTPAC grafting after DMOTPAC paid attention to the grafting outcome. In the presence of DMOTPAC grafted on the skin membrane, water transfer through the membrane is hindered, causing a drop in pressure. It appears that many DMOTPAC have been grafted onto the membrane surface, resulting in a further decrease in water flux. When the DMOTPAC attention was not more than 0.06 wt, the modified membranes showed an advantage in water flux. In Dad-HT-0.06, the water flux was 49.8 gonnecm2/h, which represents a forward progress of 16.4 gonnecm2/h compared to PA-pristine (42.8 gonnecm2/h). It might be possible to compensate to some extent the mass transfer resistance recouped from the grafting subcaste with the preface of HT nano particles. It is evident that the modified membranes exhibit analogous swab rejection as PA-pristine, which means that HT objectification and DMOTPAC grafting have not damaged the PA skin subcaste. In comparison with the pristine membrane, Dad-HT-0.06 showed a rejection rate of 99.1 in swabs [50]. Due to this, it is possible for nano particle objectification to maintain the relatively high-water flux while fictionalizing membranes based on grafting. It was physically clicked that HT nanoparticles attached to the PA matrix, and then it was covalently clicked that DMOTPAC attached to HT nanoparticles [51]. This revision system, which incorporates anti-fouling grafting and nanoparticle objectification, proved effective in achieving excellent selectivity [52].

4.1.4. Ultra-filtration membrane treatment process

UF (ultrafiltration) is the process of purifying macromolecules, colloids, and suspended patches from various results by using pressurized membrane filtration. It is also used in a number of artificial processes, such as water treatment, wastewater treatment, chemical manufacturing, and food processing, etc. [53,54]. For those who would rather have minerals in their water but still wish to remove minute impurities, ultrafiltration is the preferred filtration method. Ultrafiltration (UF) is a process that employs the same water pressure seen in a home to force water through a semipermeable membrane and eliminate impurities. Ultrafiltration, as opposed to reverse osmosis, removes bacteria, viruses, and parasites from water while retaining minerals in the water. Because a UF system uses less water to drain than a RO system, it might be chosen. After filtering, effluent water is occasionally recycled using ultrafiltration so that it can be utilized again for irrigation. In most cases, UF membranes are used to eliminate harmful organisms and nearly all colloidal particles. It is expected that the majority of the dissolved solids will pass through the membrane without causing any problems later or in the final product water. Water turbidity will be eliminated by UF for most cases. The contamination of membranes, also known as membrane fouling, is a big problem for UF. In addition to morphology, porosity, and hydrophilicity, membrane fouling depends on the face parcels of the membrane. It is becoming increasingly common to use sweats to enhance the effectiveness of UF processes [55].

In addition to their outstanding hydrolytic and thermal stability, sulfone-containing polymers, such as polyether sulfone and polysulfides (PESU), are often used in nanofiltration (NF) and UF membranes for water operation, due to their strong mechanical parcels and chemical stability [56]. It is still a major concern for real-time operations that PESU fouling, as well as the fouling of the general polymer membranes, will lead to lower flux, an increase in energy consumption, and a reduction in separation efficiency. Researchers have linked fouling to the membrane material's natural hydrophobicity. The organic foulants that are present in artificial wastewater have a natural origin. These foulants adhere to the hydrophobic membrane shells and holes and are therefore absorbed [57].

5. Role of membrane in gas separation process

The process of gas separation via a membrane is propelled by pressure, specifically the differential in pressure between the raw materials intake and the product's output. Since the membrane employed in the procedure is typically non-porous, there won't be a significant gas loss through it. The vapor/air combination can be split using selective membranes into two phases: a hydrocarbon-depleted phase (retentate) and a hydrocarbon-enriched phase (permeate), which is then condensed. Cellulose acetate (CA) compound membranes are acclimatized for implicit gas-transportation and antibacterial exertion by incorporating colourful rates (0–8wt.) of zeolite-CuO (101, ZC) compound [58]. The end behind this is to develop an anti-fouling membrane with enhanced CO_2 saturation and selection parcels. It is selective to separate gases using polymeric membranes since they are not precious and can easily be fabricated. Despite this, polymeric membranes still face limitations in terms of gas permeability versus selected gas flow [59]. The previous inorganic membranes are highly selective, permeabilise, chemically stable, and thermally stable, but have high fabrication costs and poor mechanical stability. In mixed matrix membranes (MMMs), previous inorganic components are dispersed in a polymeric matrix, combining the advantages of padding patches and polymer membranes. As part of the United States' renewable energy program enacted encyclopaedically by the Renewable Energy Standard (RES), hydrogen is given further attention as a green energy source that can be produced from natural gas, coal, and biomass. As the largest on-going bioenergy program, it is enforced encyclopaedically through the Renewable Energy Standard. The separation and/or sanctification of hydrogen from carbon dioxide can be done with an environmentally friendly membrane module designed for an airman membrane-grounded separation [60]. In light of the previous description, it is clear that mixed matrix membranes (MMMs) are utilized largely implicitly when separating hydrogen gas from carbon dioxide gas.

We investigated several inorganic membranes to get MMM with charming gas separation performance in relation to inorganic and polymeric membranes, with a few of them proving a good fit in membrane operations. A zeolitic pudding, a silica nanoparticle pudding, and a CMS pudding are probably the most extensively examined inorganic puddings [61]. As far as the shape of fly specks and chemical composition are concerned, these puddings are exaggeratedly rigid. Gas separation and sanctification are Mixed matrix membranes comprise polymeric accoutrements and puddings; they enhance membrane separation performance. By using them, sustainable development goals can be achieved, especially those related to essence-organic fabrics, since they are more environmentally friendly and require less energy than other options [62].

The membrane technology has recently emerged as an innovative and promising approach for distant chemical engineering processes such as the production of H2 products, the enrichment of oxygen, the production of biogas, the separation of hothouse feasts and the treatment of wastewater due to its innovative performance, environmental friendliness, and ease of operation. The membrane-ground gas separation (MGS) fashion for gassy fusion has been of great interest despite its modest maturity in artificial conditioning due to its colourful functional/functional advantages including simplicity, cost effectiveness, environmental friendliness, versatility, ease of scaling up, inflexibility, and modularity [63]. A considerable amount of research has been conducted on how mongrel compound membranes, which have both organic and inorganic properties, perform efficiently and cost effectively.

It is the role of the membrane employed in MGS to function as a passable pervious hedge, permitting motes of a given gas to pass through its nano/microspores, but prohibiting motes of other specific gases from entering based on their size, diffusivity, or solubility [64]. Considering the feasibility of applying these components for gas separation (especially CO2) depends primarily on their cost and effectiveness. Due to their brilliant advantages, such as negligible costs and ease of processing, polymeric membranes have become an irrefutable material for gas separation. In general-applied polymeric membranes, the permeability and selectivity of gases must be high so that the separation will be effective, and the membrane area will be reduced [65]. As a consequence of a trade-off between the two previously mentioned parameters (permeability and selectivity), new polymeric membranes are no longer developing as fast. In recent years, nanomaterials (particularly nanofibers and carbon nano tubes) have been successfully utilized for improving and optimizing the performance of various membranes [66].

5.1. Membrane in energy storage and conversion

The implementation of effective, efficient energy storage devices has become increasingly important as the world strives to move away from traditional energy sources [67]. In order to address this problem, unconventional energy storage devices like hybrid batteries, redox flow cells, and bacterial batteries are emerging. Electrochemical devices designed using these alternative cell configurations offer high energy conversion efficiency and modularity while providing flexibility in materials and operating conditions. There are a wide range of power levels among these diverse devices, ranging from a few milliwatts to several megawatts. Developing all-solid-state batteries that can cycle for long periods of time and have a high energy density makes it possible to manufacture durable electronic and point-of-care devices. In the future, earth-abundant metal ions could replace lithium-ion batteries in terms of capacity [68].

5.1.1. Membrane process in fuel cell

The term "energy cell" refers to an electrochemical device that continuously converts the chemical energy of an energy source and an oxidizing agent into electrical energy by changing the electrodes within the electrolyte" [69]. Electrochemical batteries work on similar principles to energy cells. The only difference is that chemical energy is stored outside of the cell of an energy cell, while chemical energy is stored inside the cell of an electrochemical battery. It is more efficient to generate electrical power from energy cells than through conventional approaches, which undergo multitudinous conversions before they produce actual electricity. Through the conversion of chemical energy directly into usable power and thermal energy, energy cells can achieve up to 60 effective conversions. Types of electrolyte and operating temperatures can determine how energy cells are distributed [70]. There are several types of low temperature energy cells, including alkaline energy cells (AFCs), phosphoric acid energy cells (PAFCs), polymer electrolyte energy cells (PEFCs), and direct methanol energy cells (DMFCs). The two most common forms of high temperature energy cells are solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs). In order for fuel cells to perform efficiently, proton conductivity becomes one of their backups. Proton conductivity is needed to allow the protons to move freely through the fuel cell. It also helps to minimize energy losses due to electrochemical processes. Proton conductivity is essential for fuel cell performance. Therefore, proton conductivity must be optimized to ensure optimal performance of a fuel cell. This can be done through material selection and proper design [71,72].

Electrolyte membrane continuation is not yet compatible with target applications [73]. Energy cell systems for automotive operations, for instance, require high-performance membranes that operate under conditions of low relative humidity and temperatures beyond the boiling point of water. As a result of these conditions, energy cell membrane electrode assemblies (MEA) cannot maintain a significant amount of water, limiting conductivity, among other things. In addition to their strength and stability, membranes must also be compatible with electrodes and perform well as energy cells for automotive operations across the entire temperature range: from subzero to full power (up to 120 °C–130 °C); for stationary operations at advanced temperatures > 150 °C, over periods of 5000 to 50,000 h (automotive) [74].

5.1.2. Membrane process in redox flow batteries

The redox inflow battery stores energy by oxidizing and reducing two redox couples as electroactive components [75]. An electrochemical cell mound is comprised of a number of cells connected in series or parallel so that response occurs at inert electrodes in a typical redox inflow battery with 2 electrolyte budgets and electrolytes circulated by pumps through an electrochemical cell mound. It is usually anode, cathode, and ion exchange membrane that provide prolixity of ions across the membrane as well as preventing cross-mixing of electrolyte results between these two budgets of electrolytes [76]. In a half cell electrolyte, the discharged state of the redox species is converted into the charged state during charging by applying power from an external source. The chemical energy is transformed into electricity during discharge by electrons flowing between redox species. Accordingly, the number of active redox species in the mound and electrolyte volume will determine the energy capacity of the system and the power of the system is determined by the number of cells. Therefore, a redox inflow battery behaves more like a regenerative energy cell than a conventional battery [77].

In a redox flux cell, the membrane plays an important role. A suitable membrane for redox flux systems generally requires a great deal of effort. It is ideal to have good chemical stability under acidic conditions, resistance to the highly oxidizing terrain of the positive half-cell electrolyte, low electrical resistance, low permeability to vanadium or polyhalide ions, high permeability to hydrogen ions, good mechanical parcels, and low cost in vanadium redox systems [78]. By allowing ions to transfer from one electrode to the other during current flow, the membrane of redox flux cells assists the cross-mixing of the positive and negative electrolytes. In order to commercialize multitudinous redox flux cells, the membrane has proven to be a major obstacle. A membrane used for ion exchange can be a waste product, a list, or a tube that separates two fluids and enables ions to move between them. These membranes are made up of a three-dimensional network of cross-linked direct polymer chains [79]. Water would dissolve the membrane in the absence of the cross-linking, leaving a polyelectrolyte in place. There are fixed ion functional groups on ion exchange membranes; these are combined with counterions in sufficient numbers to render the exchanger electrically neutral [80].

The number of review papers which addressed membranes in the battery system is certainly quite large, but many of these focused on the details of membrane manufacturing styles, which is not a desirable process in the exploration of membranes. Consequently, fabrication of membrane products has received relatively little attention. Microstructure and lading additions in membrane products are affected not only by the manufacturing styles but also by their cost [81]. The first section of the article introduces the bracket of membranes and their operating principles. Additionally, these membrane types are studied from a medication standpoint. A description of typical membrane medication styles follows. In the end, membrane medications are epitomized by their environmental impacts.

5.1.3. Super capacitor for electrode fabrication

When compared to other energy storage technologies like fuel cells, capacitors, and batteries, supercapacitors have several important advantages. Supercapacitors' efficiency is dependent on a number of factors that are dependent on its constituent parts. Electrolyte, separator, current collectors, and electrodes are some of these parts. A separator prevents the electrical circuit from shorting out, an electrode stores the charge, and an electrolyte supplies the necessary ions, all of which are transmitted from the electrode to an external circuit. A supercapacitor's design is greatly influenced by the material selection for the separator. Its primary job in supercapacitors is to keep the anode and cathode electrode materials apart to avoid short circuits. It primarily exists as a porous membrane to facilitate simple ion transport. Materials such as glass fibre, cellulose, ceramic fibres, or polymeric film materials are frequently utilised as separators.

A major drawback of polyvinylidene difluoride (PVDF) is that it is more prone to list action when used to manufacture electrodes for super capacitors. Binders are designed to bind active materials in electrodes and improve adhesion between electrodes and current collectors [82]. The selection of suitable binders has been guided by the quality parameters of adhesion strength, hydrophilicity, thermal and electrochemical stability, as well as non-bane properties. In addition to enhancing electrical communication between active apparatus, binders could make electrodes compact, thus facilitating a more compact arrangement. There is an enormous impact on the electrode drug and overall electrochemical performance of a super capacitor depending on physical parameters such as the attention of the binder, its cleaner, and its drying temperature [83].

These physical parameters need to be kept in mind for a nanomaterial to have a voguish electrochemical performance or to produce the maximum electrochemical parcels possible. In the case of adding a binder, attention must be paid to the rate at which the active material is added to the polymer binder, as there is an optimum rate. An excess of binder can block the pores of an active material and minimize its compact capability if the volume of binder is too low [84]. By reducing electron-transfer resistance, enhancing pseudo capacitive charging, allowing electrolyte ions to diffuse faster inside nano porous materials and reducing ion diffusion resistance, proper attention can be paid to the binding agent and active material [85].

5.1.4. Membrane process in nuclear industry

Membrane processes are thought to be promising techniques for clean technologies that minimize raw material use, optimize energy utilization, and lower waste generation. They are competent to address a wide range of environmental issues, including those pertaining to nuclear technology [86]. Many nuclear facilities around the world have used membrane methods to process liquid radioactive waste. High levels of chemical, thermal, and radiation resistance are exhibited by ceramic or composite membranes. For the concentration of radioactive waste, a thermal method known as membrane distillation using resistant porous membranes was proposed and tested [87]. Additional techniques, such as electric processes utilizing ion-exchange membranes and liquid membranes, are being developed for potential use in the nuclear sector [86]. Membrane techniques were taken into consideration as substitute approaches for recovering various recyclable and reusable materials.

5.1.5. Soil science and membrane technology

Cleaning up soils contaminated with hazardous organic and metals substances is necessary to comply with regulations. When pollutants are transferred from the solid matrix to the wash liquor during soil washing with aqueous solutions, further treatment is required [88]. These wash liquors have not been concentrated substantially using membranes. Nonetheless, a number of membrane approaches seem promising. The primary goal of these methods is to identify strategies to reduce the volume of the pollutants while still concentrating them. Acid leaching was used in conjunction with microfiltration and nanofiltration membrane techniques to improve heavy metal removal from polluted soil. Soil particles were separated from the metal-containing leachate by microfiltration. Subsequently, the leachate underwent nanofiltration processing to extract wasted acid from the slurry and decrease its volume. The bench size study's findings illustrated the benefits of using membrane processes in soil treatment procedures, which should remove metals more quickly and completely and produce less waste products overall.

5.1.6. Membrane process in food and beverage industry

Membrane technology is becoming widely used in the food sector as a processing and separation technique. Processing novel components and foods can be done with innovative technologies like membrane separations. One green technique that is being used is membrane separation [89]. Reverse osmosis and ultrafiltration membranes use energy efficiently because there is no phase change, which is one of the technology's main advantages [90]. Furthermore, high pressure can be used to reverse the flow direction of the food solution to obtain the desired concentration without compromising nutrition quality. Low molecular weight solutes such as salts, monosaccharides, and fragrance chemicals are extracted from food products using this approach. This membrane technology can be used to concentrate and purify fruit juices, enzymes, fermented liquors, and vegetable oils, among others. Membrane processes driven by pressure make it easier to separate components with a wide variety of particle sizes. This explains why the food processing sector uses them in a variety of ways [91].

6. Role of composite membrane in biomedical applications

In the clinical field, manufactured membranes play a crucial role across various applications, showcasing their versatility and importance in medical technology [92]. Five key applications include haemodialysis, where membranes function as artificial kidneys to remove waste products and excess fluid from the blood of patients with renal failure [93]. These membranes must possess high permeability to small solutes while selectively retaining larger molecules like proteins. Blood oxygenators utilize membranes to facilitate the transfer of oxygen into the bloodstream while removing carbon dioxide, making them essential in cardiac surgeries and during organ transplants [94]. Another significant application is in controlled drug delivery systems, where membranes regulate the release of therapeutic agents, ensuring sustained and targeted delivery, thereby enhancing the efficacy of treatments and minimizing side effects. Artificial organs, such as heart valves and vascular grafts, often rely on specialized membranes to mimic the function of natural organs, requiring biocompatibility and mechanical strength to withstand physiological conditions [94]. Lastly, in tissue engineering, membranes serve as scaffolds for cell growth and tissue regeneration, necessitating specific characteristics such as porosity and biocompatibility to support cell attachment and proliferation. Each of these applications necessitates a thorough understanding of membrane types, their performance characteristics, and the challenges they face, such as fouling, biocompatibility issues, and long-term stability [95]. Addressing these challenges is essential for advancing the field of medical membranes and improving patient outcomes in various therapeutic contexts. Following are some important applications in medical fields **(Figure 2)**.

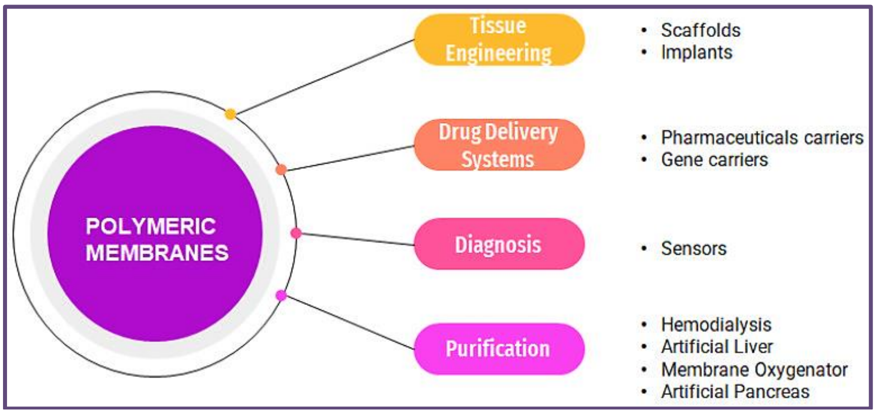

Figure 2. Applications of polymeric membranes in biomedicine [96].

6.1. Haemodialysis through membrane

Because of the continually evolving criteria for selectivity and the upgrading of materials developed to meet these objectives, the field of membrane materials is among the most dynamic. Artificial kidneys are made of membrane materials such as polyacrylonitrile (PAN), polysulfone derivatives (PSU), and cellulose derivatives. Desalination and hemodialysis are the two membrane processes that are currently necessary for daily living rather than for development. Tens of millions of people with chronic renal disease have benefited from hemodialysis during the past 60–70 years, both in terms of life preservation and enhanced longevity. It is fundamental for those whose kidney has fizzled and are as of now not ready to control the body’s garbage removal [97]. Failure of the kidneys to remove harmful wastes may result in elevated blood pressure, excessive fluid retention, and insufficient red blood cells.

It can provide electrolyte replacement and re-establish pH levels and remove side effects associated with kidney disease. Dialysis is an effective way to replace a portion of the elements found in the kidneys. A semi-permeable dialysis film is used to collect blood from the patient, which is then flooded with saline that has salt, potassium, and calcium concentrations comparable to the patient’s blood. A concentration gradient across the membrane transports urea and other low-molecular-weight metabolites to the dialysate. Proteins and blood cells, which are larger components in the blood, are prevented from diffusing. The dialysis membrane underwent various module design phases. The empty fiber frameworks are the most ruling on the lookout and the cost for these dialyzers are generally low since they are made in mass. The dialyzer can be easily refilled with as little as 60to 100 milliliters of blood, which is an appealing feature of this design. Significant metabolic products such as urea and creatinine are efficiently eliminated by the cellulose layer, while metabolites with sub-atomic loads exceeding 1000 are less successfully removed [98]. In the following years, there has been a need to view such material as elective. It has become more common to replace cellulose with synthetic polymers due to their tendency to stimulate normal kidney function more closely. There are a number of substances that can be substituted for cellulose, including polyacrylonitrile, polysulfide, polycarbonate, polyamide, and polysulfide. Synthetic Fiber membranes are composed of finely micro porous skin layers on their inner surface that contact the blood. Membranes made from these fibres have a tenfold increase in hydraulic permeability compared to those made from cellulose [99].

6.2. Blood oxygenators through membrane

Blood oxygenators are utilized during a medical procedure when the patient's lungs can't work regularly. In the 1930s, pioneering work on these devices was done. This mechanical device was made to look like the heart and lungs so that it can be used for surgery on the heart and its great vessels [99,100]. Artificial lungs, or blood oxygenators, have long been recognized as a potential use for membrane contactors. In fact, the ability to exchange gases without the production of bubbles is vital to avoid surgical complications. The oxygenator's lung-like function is to remove carbon dioxide from the blood and expose it to oxygen. It is disposable and has 2–4 square meters of hollow fiber-shaped membrane that is permeable to gas but impenetrable to blood. Within the hollow fibers, oxygen travels in the opposite direction from that of blood on the outside. Blood oxygenators have a special design, and materials must meet strict requirements for their suitability for use in medicine. Dense or porous hydrophobic membranes are suggested as alternatives.

In the human lung, the all-out trade film region between the blood vessels and the air attracted and out is around 80 m^2. The membrane of the human lung is thought to be about 1 mm thick, and the lungs, total exchange capacity is much greater than what is typically required. This permits individuals with debilitated lung ability to have generally typical existences. Micro porous poly-olefin fibers are now utilized, whereas silicone rubber membranes were utilized in the initial membrane oxygenators. Drop through the device to maintain good mass transfer with minimal pressure. Most of the time, the outside of the fibers is where blood circulates. This method, on the other hand, does more harm than good when used for extended periods of time. Generalized enema, thrombocytopenia, coagulopathy, hemolysis, and impairment of organ function occur [101].

6.3. Controlled discharge drugs through membrane

Every osmotic medication delivery method has an osmotic core and a semi-permeable membrane that regulates water flow. The medicine is exclusively discharged in solution form, and it has a single orifice. Only works with medications that dissolve in water. The composite membrane may successfully encourage PC-12 cells to develop into neurons and has good biocompatibility [102]. Furthermore, there would not be any more harm done when the composite membrane is placed directly to the damaged areas [102]. A medicine should be delivered to a specified location at a given time with a certain release pattern in an ideal medicine delivery system. The pharmaceutical supply provided by conventional medical forms (tablets, injection outcomes, etc.) often soars over the required cure. The primary hurdles for all delivery systems are maintaining medication positions in the bloodstream or releasing medication gradually to prevent repeated doses and hepatic "first-pass" processing around the medication [103].

In control drug delivery systems, a membrane controls the rate at which the drug is delivered to the body. In certain gadgets the film controls penetration of the medication from a supply to accomplish the expected medication conveyance rate. Different gadgets utilize the osmotic strain created by dispersion of water across a layer to control smaller than usual siphons. In other devices, the drug is embedded in the material of the membrane, whereupon it slowly dissolves or breaks down in the body. After that, a combination of diffusion and biodegradation is used to control drug delivery. The target of these gadgets is to convey a medication to the body at a rate foreordained by the plan of the gadget and free of the changing climate of the body. Only the total amount of medication administered to a patient is controlled in conventional medications [104].

6.4. Artificial organs through composite membranes

The amazing advances in artificial organs (AO) technology are becoming more and more significant in today's medical procedures. By keeping physiochemical gradients within a safe range, AO technology can now partially enhance the activities of human organs. To support the failing organs' chemical and physical activities, many of these artificial organ replacements use synthetic polymeric membranes. Artificial kidney, liver, pancreas, and lung are among the specific AOs that use membrane technology. While the technology for artificial kidneys is clinically mature, there are still numerous unresolved technical issues with other membrane-based AOs such pancreas, liver, and lung. Such problems are undoubtedly extremely complicated and call for multidisciplinary cooperation within the domains of chemistry, biology, materials science, and engineering. Furthermore, even with improvements, the quality of life remains low for people with organ failure. To enhance patient well-being and quality of life, AO technology needs to be continuously improved from both a membrane and a biocompatibility standpoint [105].

In the early 1900s, the bubble oxygenator was a popular artificial lung bias. The use of membranes prevented unintended haemolysis and air emboli, which were induced by bubble oxygenators. In addition to continuously improving permeance performance, multilayer flat distance membranes were reduced to about 2 m^2 per concave fibre membrane as a result of continuous improvement in membrane permeance performance. As of now, blood oxygenation effectiveness is limited by blood side mass transfer resistance rather than membrane gas transport performance [94]. In general, there are two types of artificial lung technology: short-term and long-term respiratory aids. Approximately 1.5 million open heart bypass surgeries are performed every year as short-term support. A cardiopulmonary bypass device, also known as a heart-lung machine, circulates venous blood from the case extra-corporeally, or outside the body [106]. During the oxygenation process, the blood is put back into the shell after having been oxygenated inside an oxygenator. It is aimed at temporarily integrating the functions of the heart and lungs during the approximately six-hour procedure [107]. A long-term respiratory support system called extracorporeal membrane oxygenation (ECMO) is used to provide this support. This medication is only approved for patients with severe lung failure caused by advanced age, long-term lung illnesses, or recent viral infections. As a primary objective, ECMO systems are intended to sustain the patient until their own bodies can heal. The fact that it can raise patient survival rates by as much as 75%, when compared to traditional treatments, has repeatedly demonstrated its efficacy.

6.5. Tissue engineering through membrane

The field of tissue engineering is expanding in order to create novel technologies aimed at effectively treating degenerative disorders that impact various kinds of connective tissues [108]. In recent years, there has been a tremendous increase in the search for materials that are biocompatible, bioactive, biodegradable, and multifunctional [109]. Because of their high-water retention capacity, biocompatibility, and degradability, natural polymers including hyaluronic acid, collagen, and chitosan provide excellent materials for tissue engineering composites. The combination of chitosan, collagen, and calcium phosphates as composite materials satisfies the necessary requirements and may produce bio stimulation for tissue regeneration [109,110]. After 48 hours, the chitosan membranes with the largest amounts of collagen and hydroxyapatite showed the highest levels of cell attachment. Good cell adhesion and little cytotoxicity were demonstrated by all composite membranes, indicating a high degree of potential for these materials as biomaterials for tissue engineering [111–113].

7. Challenges of composite membranes

Synthetic composite membranes face significant challenges that impede their performance and widespread adoption across various applications, including water treatment and pharmaceuticals [114]. One of the primary issues is membrane fouling, which occurs when particles, organic matter, or microorganisms accumulate on the membrane surface, leading to reduced permeability, increased energy consumption, and the need for frequent cleaning. Fouling can be categorized into organic, inorganic, and biofouling, each requiring specific mitigation strategies such as pre-treatment, surface modification, and advanced cleaning protocols [115]. Stability is another critical challenge, with membranes needing to maintain chemical, thermal, and mechanical integrity under operational conditions. Degradation from aggressive chemicals or varying temperatures can compromise membrane performance, while long-term use may lead to changes in permeability and selectivity [116]. Additionally, scalability presents hurdles in transitioning from laboratory-scale to industrial applications, as achieving consistent manufacturing quality, controlling production costs, integrating new technologies into existing systems, and complying with regulatory standards are all vital considerations [116]. Addressing these challenges through ongoing research and innovation in membrane materials, designs, and production methods is essential to unlocking the full potential of synthetic composite membranes in various industries [117]. So, the composite membranes should focus on developing novel polymers, nanocomposites, and hybrid structures to enhance permeability, selectivity, and fouling resistance. Advanced surface modification techniques and innovative coatings can improve hydrophilicity and anti-fouling properties, while 3D-structured and layered designs may facilitate better mass transfer. Exploring scalable manufacturing methods and efficient fouling mitigation strategies, such as intelligent membranes with real-time detection, will be crucial for extending membrane lifetimes [23]. Integrating membranes with renewable energy and biological processes can enhance sustainability. Additionally, conducting life cycle assessments and tailoring membranes for specific applications will optimize performance and meet the growing demands in water treatment and healthcare.

8. Future perspectives

Water treatment applications have proven to be successful with membranes, and membrane technology continues to advance. Fouling and chemical stability of membranes are two major problems that still need to be addressed [118]. As membranes' operational lifetimes are extended and their energy requirements are reduced, they will become even more cost-effective. This area of research has focused on the modification of membrane surfaces and improving pretreatment of the feed water before it reaches the membranes. Additionally, membranes are being studied for chemical stability. Through improved tolerance to chlorine, the poly amide TFC membrane could be operated at lower costs by eliminating pretreatment dichlorination. There are new applications of membranes for water purification in addition to wastewater treatment and desalination. In the oil and gas industry, produced water is purified, which is water that is generated during production. Many of these waters are contaminated with oils and salts, so they cannot be used for beneficial purposes [119]. Water produced from oil and gas production often occurs in arid regions, making membranes capable of removing hydrocarbons and salt an excellent source of water. There has been an enormous advance in the membrane field as a whole. The advantages of membranes for water purification applications include being economical, environmentally friendly, versatile, and easy to use [57].

In terms of desalination, nano-based composite membranes can be a promising option; however, there are still many research requirements to be addressed. Toxicology of nanoparticles and health risks associated with adding nanoparticles during manufacturing must be fully understood [39]. It is a demanding concern to address the durability of fillers inside membranes, despite various nanoparticles being incorporated as fillers inside the polymer matrix. In the future, nanomaterial-based composite membranes may be a promising option for seawater pre-treatment, but mechanisms and technologies need to be developed so that nanomaterial toxicity can be estimated cost-effectively on living and non-living organisms.

Due to the very thin graphene-based composite membranes, separating the membrane from the substrate is challenging. In order to improve the permeation of graphene-based membranes, a lot of research is required [120]. The best material for making composite membranes is polymeric-based membranes for desalination. It is essential to continuously research and develop polymeric membranes to address bio fouling and chlorine resistance. The resistance to chlorides of TFC membranes needs to be improved through research and development [121]. In order to improve chlorine resistance, the di-chlorination step can be eliminated to decrease overall costs. The mass production of graphene oxides and the ease of functionalizing graphene oxides make graphene-based composite membranes inexpensive [122]. Although the use of composite membranes has been widespread, still the issues stated in the manuscript need attention for these to serve as perfect alternatives for seawater pre-treatment [39].

9. Conclusions

Finally, it has been determined that composite membranes have a wide range of contemporary uses that are amazing and still expanding. Utilising membranes to create process water from surface water, groundwater, or wastewater is becoming more and more common. Nowadays, membranes are competitive with traditional methods. Membranes can be employed as catalysts in syntheses or for gas storage in biogas plants in addition to being utilised for filtering, extraction, and distillation. Among the industries that heavily rely on membrane filtering technology are the ones treating water and wastewater, processing food and beverages, pharmaceuticals, and medical applications. This review article has covered a wide range of membrane application processes, with a classification of these applications based on the characteristics of the membrane.

Pharmaceuticals, chemicals, medicines, and industrial processes need clean water, which can be achieved with water filtration. There are a few most popular and simple techniques for purifying water. These include solar purification, UV radiation, iodine addition, gradual sand filtration, water purification, water chlorination, boiling water, and more. There have been many different techniques used to purify water throughout history. There are many techniques used in wastewater treatment, including physical processes like filtration, sedimentation, and distillation, biological processes like biologically active carbon and slow sand filters, chemical processes including flocculation and chlorination, and the use of electromagnetic radiation, including ultraviolet light. It is possible to lower dissolved and particulate matter, as well as parasites, bacteria, algae, viruses, and fungus concentrations by purifying water.

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