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Polymeric Membranes for Brackish Water Treatment: Article Review

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Abstract: Drinking water scarcity is an ever-increasing global concern, particularly for countries lacking access to seawater resources or rivers, where brackish water represents the primary available source. Brackish water often contains a complex mixture of impurities, salts, and mineral elements, and its treatment is further complicated by the presence of landfill leachates, agricultural contaminants (such as pesticides, herbicides, and fertilizers), and rural pollution. As a result, there is a critical need to develop effective purification methods. Among the available technologies, membrane based desalination has emerged as a leading solution, with membrane separation accounting for more than half of the global desalination capacity. Polymeric membranes along with ceramic and composite alternatives are widely used in brackish water treatment due to their high selectivity, cost-effectiveness, and adaptability. To improve water flux and reduce fouling, inorganic materials are often embedded into polymeric solutions, including nanofiber and nanomaterial enhanced membranes. This review focuses on water challenges and brackish water distribution in Egypt, offering a comprehensive analysis of membrane technologies, including materials, fabrication techniques, fouling behavior, membrane modules, and filtration processes. Furthermore, it highlights the main types of polymeric membranes reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) and assesses their effectiveness in removing common contaminants. Recent advancements in membrane materials and hybrid treatment systems are also explored, providing insight into emerging trends and future directions for sustainable brackish water treatment.

Keywords: Polymeric membranes, Brackish water treatment, Ground water, Water purification, Membrane fouling, Contamination removal.

1 Introduction

Water scarcity is one of the most critical global challenges, driven by rapid population growth, industrialization, and climate variability [1]. As freshwater sources become increasingly stressed, brackish water, with total dissolved solids (TDS) between 1,000 and 10,000 mg/L, is being explored as an alternative for drinking water and irrigation [2]. However, its treatment is complicated by the presence of diverse pollutants, including dissolved salts, organic matter, and heavy metals such as iron (Fe) and manganese (Mn) [3].

Brackish water is a vital source of drinking water in many regions around the world; however, it often suffers from contamination due to both natural and anthropogenic sources. Common pollutants in groundwater include iron (Fe^{2+}) and manganese (Mn^{2+}), which occur naturally in aquifers but can exceed the World Health Organization (WHO) permissible limits, leading to undesirable taste, discoloration, pipe clogging, and bacterial growth. Ammonia, often linked to agricultural runoff and industrial discharge, is another problematic contaminant that may cause toxicity in aquatic environments and interfere with disinfection processes. In addition, nitrates, fluoride, arsenic, and heavy metals such as lead, cadmium, and chromium can pose serious health risks if present above

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regulatory limits, including neurological damage, kidney problems, and even cancer. Salinity and total dissolved solids (TDS) are also significant concerns in brackish groundwater, affecting taste, agricultural suitability, and long-term health. Addressing these pollutants is essential to ensure the safety, usability, and sustainability of brackish water resources. Brackish water requires effective treatment before use in drinking, agriculture, or industrial applications [4]. Polymeric membranes have emerged as a promising solution due to their high selectivity, permeability, and cost-effectiveness.

Conventional treatment techniques such as oxidation-filtration, ion exchange, chemical precipitation, and adsorption are commonly used to remove Fe and Mn from groundwater. While these methods are effective to some extent, they often suffer from limitations such as incomplete removal at low concentrations, high chemical demand, complex operation, and the generation of secondary waste [5].

The removal of manganese (Mn) and iron (Fe) from brackish water presents a major challenge due to their variable chemical states and interactions with other constituents. While conventional techniques such as oxidation, precipitation, and filtration are commonly employed, polymeric membrane technologies offer a more compact and efficient alternative, particularly when integrated into hybrid systems that combine oxidation and membrane separation. Ultrafilters and nanofilters, especially when combined with pre-oxidation steps, have demonstrated high efficiency (over 90%) in removing Fe and Mn from groundwater. Studies using membrane technologies have shown that gravity-driven ultrafiltration systems pretreated with manganese oxide (MnO_x) layers can achieve up to 95% removal of Fe and over 60% Mn removal in early stages, stabilizing after startup; similarly, RO systems consistently achieve >90% removal, backed by strong evidence in water treatment research [6].

In contrast, membrane-based technologies have emerged as promising alternatives due to their smaller footprint, lower chemical consumption, modular design, and ability to remove multiple contaminants simultaneously including dissolved salts, heavy metals like iron and manganese, organic compounds, and even ammonia. Among them, polymeric membranes are widely employed due to their tunable structure, relatively low cost, and chemical compatibility. These technologies differ in their separation mechanisms and pore sizes, and each type utilizes specific polymeric materials that influence the membrane's performance, stability, and resistance to fouling[7,8].

Microfiltration (MF) membranes are primarily used to remove suspended solids, turbidity, bacteria, and oxidized forms of metals like iron and manganese. The polymers commonly used for MF membranes include polyvinylidene fluoride (PVDF), known for its excellent chemical resistance and mechanical strength, polysulfone (PSf), which offers good thermal stability, and polypropylene (PP), which is a low cost and chemically resistant option. These membranes typically act as pretreatment barriers in more complex filtration systems [9].

Ultrafiltration (UF) membranes have smaller pores than MF and are effective at removing viruses, colloids, proteins, and oxidized metal hydroxides. UF membranes are often made from polyethersulfone (PES), a highly hydrophilic polymer when combined with additives, making it one of the most widely used polymers in UF applications. Polysulfone (PSf) is also common, often blended with hydrophilic agents like polyethylene glycol (PEG) to improve water permeability and reduce fouling. Other polymers include cellulose acetate (CA), which is biodegradable and less prone to fouling, and polyacrylonitrile (PAN), valued for its strength and chemical resistance in aggressive water matrices [10].

Nanofiltration (NF) membranes operate at higher pressures and remove divalent ions (such as calcium and magnesium), organic molecules, and partially reject monovalent ions like sodium and chloride. NF membranes are typically thin-film composite (TFC) structures, consisting of a selective polyamide (PA) layer deposited over a porous support layer made from polysulfone (PSf) or polyethersulfone (PES). The PA layer provides high rejection of salts and organics while maintaining reasonable flux, making NF suitable for groundwater sources with moderate salinity and organic pollution [11].

Reverse Osmosis (RO) membranes are the tightest of all membrane types and can remove nearly all dissolved species, including ammonia, nitrate, heavy metals, and salts, making them ideal for brackish and highly contaminated groundwater. Like NF, RO membranes are typically made as TFC structures, where the top selective layer is a highly cross-linked aromatic polyamide (PA). The underlying support layers are commonly made of PSf or PES. Cellulose acetate (CA) membranes are also used in some low-pressure RO applications, though they have largely been replaced by TFC membranes due to their higher flux and better chemical resistance [12].

RO and NF membranes are particularly suitable for removing dissolved ions and heavy metals, while UF and MF are efficient in eliminating colloids, pathogens, and suspended solids [12]. The most common materials which are used in membrane fabrication include polyethersulfone (PES), polysulfone (PSF), polyvinylidene fluoride (PVDF), and polyacrylonitrile (PAN) due to their mechanical strength and chemical stability [13].

The polymeric materials used in membrane fabrication vary in their surface properties, which significantly influence membrane performance, particularly in terms of water permeability, fouling resistance, and selectivity. These materials can be broadly classified as hydrophilic or hydrophobic. Hydrophilic polymers, such as polyvinyl alcohol (PVA), cellulose acetate (CA), and chitosan, are easily wetted by water and tend to exhibit lower fouling tendencies, making them suitable for applications requiring high water flux and biofouling resistance. In contrast, hydrophobic polymers like polysulfone (PSf), polyethersulfone (PES), and polyvinylidene fluoride (PVDF) offer excellent chemical and thermal stability but are more prone to fouling. To overcome this limitation, hydrophobic polymers are often modified by blending with hydrophilic additives such as polyethylene glycol (PEG) or surfactants like Tween 20 to enhance membrane wettability and reduce fouling [14].

In addition to single-material membranes, blended membranes have been developed by combining different polymers to achieve a balance of desirable properties, such as improved permeability, mechanical strength, and fouling resistance. Moreover, composite membranes represent a more advanced category, typically consisting of a thin selective layer (e.g., polyamide) deposited on a porous support layer (e.g., PES or PSf). These membranes offer high separation efficiency and can be further enhanced by incorporating functional materials such as nanoparticles (e.g., CuO, TiO_2) or conductive polymers (e.g., polyaniline) to improve antibacterial properties and the selective removal of heavy metals like iron and manganese [15].

This review aims to provide a comprehensive overview of the application of polymeric membranes for the treatment of brackish water. It covers the types and properties of common polymeric membranes, the physicochemical characteristics of brackish water and its pollutant categories, and mechanisms for iron and manganese removal. It also highlights the recent advancements in materials and hybrid membrane system. By addressing current trends and challenges, this review offers valuable insights into the development of effective and sustainable solutions for brackish water treatment.

In light of these challenges, future work is directed toward developing advanced membrane materials with enhanced selectivity, permeability, and fouling resistance. One promising approach is the use of electrospinning technology to fabricate nanofibrous membranes with high surface area, interconnected pore structures, and tunable properties. Electrospun membranes offer the potential for improved removal of contaminants such as iron, manganese, and ammonia, especially when functionalized with nanoparticles or conductive polymers. This technique enables better control over membrane architecture and surface chemistry, paving the way for next-generation membranes tailored for efficient and sustainable groundwater treatment.

2 Brackish water

Brackish water is defined as water containing a total dissolved solids (TDS) concentration between 1,000 and 10,000 mg/L. Its salinity is higher than that of freshwater (less than 1,000 mg/L) but significantly lower than seawater (which typically exceeds 35,000 mg/L). This intermediate salinity can arise either naturally or as a result of human activities. In addition to salts, brackish water may also contain various other contaminants, including iron, manganese, nitrates, ammonia, as well as agricultural pollutants (such as pesticides and fertilizers) and organic matter [16].

Brackish water represents a significant portion of the world's non-fresh groundwater resources. It is especially abundant in arid and semi-arid regions, such as parts of India, the Middle East, North Africa, and the southwestern United States. It is also common in coastal areas, where seawater intrusion mixes with groundwater. Brackish water is widely used for desalination, particularly for drinking water and agricultural purposes, as well as in various industrial applications such as cooling, washing, and processing. Globally, common treatment methods include membrane-based technologies like reverse osmosis (RO) and nanofiltration (NF), often combined with hybrid systems to improve efficiency. For example, the state of Texas in the United States relies heavily on brackish groundwater desalination to supply drinking water in dry areas, while India has launched national programs to desalinate brackish water for agricultural use.

In Egypt, brackish groundwater is widely distributed across several regions and plays a critical role in supplementing the limited freshwater resources. It is commonly found in the oases and desert areas of the Western and Eastern Deserts, including locations such as Farafra, Kharga, Siwa, Toshka, and El-Owainat. The salinity of water in these aquifers is often attributed to geological formations and salt deposits, making the water partially or fully brackish. In the northern Nile Delta, especially in Kafr El-Sheikh, Beheira, and Damietta, seawater intrusion has led to significant salinization of groundwater. Similarly, the Suez Canal zone and the Sinai Peninsula are characterized by relatively saline well water, which is primarily used for agriculture after treatment. However, Egypt faces several challenges related to brackish water use, including increased salinity due to over-extraction, seawater intrusion, and the presence of contaminants like iron, manganese, and nitrates in some aquifers. There is an urgent need for cost-effective and efficient treatment technologies. In response, national efforts have been made to establish small-scale RO desalination units in oases and Sinai, promote research on membrane-based treatment, and explore the reuse of brackish water for irrigation through advanced technologies such as hybrid membranes and modified polymeric membranes (e.g., PES/CuO). These initiatives aim to enhance water security and support sustainable agricultural development in water-scarce regions [15].

Due to the moderate salinity level of brackish groundwater, it is generally categorized into two sub-classes of groundwater resources (wells and aquifers) and surface water resources (rivers and lakes). Brackish water is generally easier to treat than saline seawater due to its lower pollution extent. However, each subclass has distinct characteristics. Brackish groundwater tends to be more saline compared to surface water, with salinity levels increasing as groundwater depth increases. Additionally, underground resources typically contain higher concentrations of mineral elements. On the other hand, due to exposure and biological activity, surface brackish water often contains a higher load of pathogenic organisms and biological contaminants. Brackish water generally contains a variety of impurities, including common salts like sodium chloride, natural organic matter (NOM), and heavy metals [17]. Different types of brackish groundwater classified based on their origin and level of contamination. Some types arise when fresh groundwater becomes saline due to interaction with salt-rich geological formations. Others form when saline water mixes with fresh water in aquifers, often caused by over-pumping or poorly constructed wells that allow water from different layers to mix. In shallow, unconfined aquifers, contamination may result from agricultural runoff, industrial discharges, or construction activities. Additionally, some deep and isolated fossil aquifers naturally contain brackish water due to their ancient geological history [18].

3 Brackish water Contaminations

In brackish water, pollutants often reach concentrations that significantly exceed drinking-water standards. For example, a study in coastal aquifers of Indonesia found iron (Fe^{2+}) levels ranging from 0.10 to 252 mg/L, with an average of 10.3 mg/L, and manganese (Mn^{2+}) ranging from 0.02 to 21.6 mg/L, averaging 3.6 mg/L notably, these levels frequently surpass the WHO limits of 0.3 mg/L for Fe and 0.1 mg/L for Mn. Nitrate (NO_3–N) was also measured between 0.01 and 5.2 mg/L, with an average of 0.4 mg/L, still below the 10 mg/L EU standard but varying regionally. Sulfate (SO_4^{2-}) levels ranged broadly from 0.2 to 3,117 mg/L, averaging 469 mg/L, with many sites exceeding the 400 mg/L threshold used in Indonesian regulations. While data on heavy metals like lead (Pb) and chromium (Cr) are less consistently reported in brackish water, global assessments indicate Pb concentrations often fall between 0.01 and 0.40 mg/L, and Cr can reach tens of µg/L in some agricultural aquifer [19]. Table 2 summarize the most pollutants in brackish water.

Table 1: Summary of Pollutant Categories in Brackish Water.

Category	Examples	Membrane Solutions
Heavy metals	Fe, Mn, As, Cd, Pb	UF, NF, RO + Oxidation
Major ions	Na^+, Cl^-, SO_4^{2-}, Ca^{2+}	RO, NF
Nutrients	NO_3^-, PO_4^{3-}	NF, RO
Organic compounds	NOM, pesticides, pharmaceuticals	UF, NF, activated carbon + membranes
Microorganisms	E. coli, viruses, protozoa, algae	UF, MF + Disinfection
Emerging contaminants	EDCs, ARGs, nanoparticles	RO, hybrid membranes + AOPs

4 Physicochemical Properties of Brackish Water

The physicochemical characteristics of brackish water significantly influence the choice and efficiency of treatment methods, especially membrane-based processes. These characteristics vary based on source, depth, and surrounding environment, but common properties include:

4.1 Total Dissolved Solids (TDS)

TDS is the primary defining parameter for brackish water. It includes various dissolved salts such as chlorides, sulfates, bicarbonates, sodium, calcium, magnesium, and potassium. The TDS levels affect osmotic pressure during membrane filtration, requiring higher pressure and energy as salinity increases. High TDS also accelerates membrane scaling and reduces flux.

4.2. pH

The pH of brackish water typically ranges from 6.5 to 8.5, though it may vary depending on CO_2 content, mineral dissolution, or pollution. pH influences metal solubility, oxidation reactions (e.g., for Fe and Mn removal), and the stability of polymeric membranes [43]. For example, low pH promotes iron solubility, while higher pH supports iron and manganese precipitation.

4.3 Hardness

Brackish water often contains high concentrations of calcium and magnesium, contributing to water hardness. Hardness can cause scaling in membranes and pipes, especially in reverse osmosis (RO) systems, thus requiring antiscalants or softening pretreatment.

4.4 Turbidity and Suspended Solids

Turbidity in brackish water results from the presence of fine clay particles, organic matter, silt, or biological growth. High turbidity increases membrane fouling, particularly in ultrafiltration (UF) and microfiltration (MF) systems. Pretreatment using coagulation, filtration, or sedimentation is often essential.

4.5. Dissolved Oxygen (DO)

Brackish groundwater usually contains low DO levels, which can influence the oxidation state of metal ions. For instance, Fe^{2+} and Mn^{2+} dominate under anoxic conditions and must be oxidized before removal by filtration membranes. Artificial aeration or chemical oxidation is often required as a pretreatment.

4.6 Specific Ion Composition

Certain brackish sources may be rich in toxic ions such as fluoride, nitrate, boron, or arsenic. These require selective removal technologies, and in some cases, multiple membrane stages or hybrid systems (e.g., RO + ion exchange).

4.7 Temperature

Temperature impacts membrane permeability, viscosity of water, and solute diffusion rates. Higher temperatures generally increase flux but may degrade polymeric membranes if they exceed the thermal tolerance of the material (typically 35–45°C for standard polymer membranes) [20].

Table 2: properties of Brackish water

Parameter	Typical Range	Impact on Treatment
TDS	1,000–10,000 mg/L	Defines osmotic pressure; affects energy use
pH	6.5–8.5	Influences solubility and oxidation
Hardness (Ca^{2+}, Mg^{2+})	50–500 mg/L	Causes scaling; requires pretreatment
Turbidity	1–50 NTU	Leads to membrane fouling
DO	0.5–6 mg/L	Affects Fe/Mn removal strategies

Parameter	Typical Range	Impact on Treatment
Temperature	15–35°C	Alters permeability and membrane performance

5 Traditional brackish water Treatment Methods

Brackish water is often contaminated with a wide range of pollutants, including heavy metals like iron and manganese, natural organic matter (NOM), nitrates, ammonia, and sometimes even pathogens. Traditional treatment methods are typically designed to target specific contaminant such as oxidation and filtration for iron and manganese, or activated carbon for organic compounds but they rarely address all pollutants simultaneously. As a result, no single conventional method can ensure complete purification. This limitation has led to the development and application of integrated or advanced treatment technologies to meet modern water quality standards [21]**.**

Historically, conventional methods such as aeration, oxidation (with chlorine, potassium permanganate, or ozone), sedimentation, lime softening, and sand filtration have been widely used to treat groundwater. For instance, aeration alone can oxidize dissolved iron (Fe^{2+}) by up to ~90%, but only achieves around 30% manganese removal when initial concentrations are about 1.5 mg/L Fe and 1.0 mg/L Mn at pH 7.0. Adding chlorine can push iron removal to 100% and manganese to 90% at pH > 9, while potassium permanganate (PP) achieves 100% Fe removal and 90% Mn removal at pH 7 using ~2 ppm dosage [22].

Iron (Fe^{2+}) and manganese (Mn^{2+}) are frequently detected in groundwater across many regions, often exceeding the World Health Organization's (WHO) permissible limits. Their presence leads to various aesthetic and operational problems, including discoloration, metallic taste, pipe scaling, and the promotion of bacterial growth within distribution systems. Traditionally, removal of these metals has relied on oxidation processes such as aeration and chlorination, followed by filtration. While effective, these methods can be energy intensive and may result in undesirable chemical byproducts [23].

To address these limitations, researchers have explored the use of alternative low-cost materials, particularly natural adsorbents and modified clays such as zeolite, sand, activated carbon, and limestone. These materials are not only cost effective but are also readily available in developing regions. Their performance, however, is strongly influenced by factors such as particle size, surface area, pH, and the initial concentration of iron and manganese [24].

In parallel, nanomaterials have emerged as powerful candidates for enhancing removal efficiency due to their high surface area and reactivity. Nano-adsorbents such as nanoscale iron oxides, manganese oxides, carbon nanotubes, and nano-zero-valent iron can remove contaminants more rapidly and at lower concentrations compared to traditional materials. However, despite their effectiveness, nanomaterials present challenges including concerns over environmental toxicity, higher production costs, and difficulties in regeneration and reuse [25].

Limestone filters especially when combined with iron-oxidizing bacteria (IOB) remove about 78–87% of iron and 77–83% of manganese, depending on conditions and operating time. For example, limestone alone achieved ~77.7% Fe removal and 82.6% Mn removal, while adding IOB increased these to ~81.7% and 83.6%, respectively [26] Similarly, batch tests with calcium carbonate media showed >90% iron removal and ~70% manganese removal at optimal dosage (~40 g per 200 mL) [27].

Lime softening (raising pH via $Ca(OH)_2$) has effectively precipitated calcium and magnesium, while also aiding removal of iron, manganese, radium, and arsenic through flocculation [28].

Denitrification in brackish water using sulfur/limestone filters has demonstrated over 95% nitrate removal, with influent nitrate concentrations of 30-94 mg/L and retention times up to 33 days [29].

Despite these successes, traditional techniques often fall short of guaranteeing removal of trace pollutants, emerging contaminants, or meeting modern water quality norms particularly for low concentration manganese or microbial contaminants. To overcome the limitations of single-method systems, hybrid approaches that combine adsorption with oxidation or filtration have shown promising results in laboratory studies. Nonetheless, the implementation of these technologies at the pilot or field scale remains limited, particularly in rural and low-income communities.

Looking forward, there is a pressing need for the development of sustainable, affordable, and efficient technologies for iron and manganese removal. Future research should prioritize the optimization of natural and nano-based adsorbents, investigate regeneration methods, and validate these solutions through real-world pilot studies [30].

The choice of membrane material and any surface modifications significantly influence the removal efficiency of Fe and Mn. Hydrophobic membranes are more prone to fouling, whereas hydrophilic modifications enhance resistance to metal oxide accumulation. Recent advancements include the incorporation of metal oxide nanoparticles such as CuO, TiO_2, and ZnO to improve antifouling properties and promote oxidative degradation. Additionally, functional polymers like polyaniline (PANI), chitosan (CS), and polyethylene glycol (PEG) have been explored to enhance the adsorption of metal ions. Techniques such as surface grafting and polymer blending are employed to introduce reactive sites that facilitate the binding or oxidation of Fe and Mn, thereby improving membrane performance and longevity in challenging brackish water treatment applications [31].

Pretreatment and Hybrid Systems for the optimal removal of iron and manganese from brackish water typically necessitate a multi-barrier treatment strategy. Initially, a pre-oxidation step using oxidants such as potassium permanganate ($KMnO_4$), sodium hypochlorite (NaOCl), or ozone converts the soluble Fe^{2+} and Mn^{2+} ions into insoluble oxide forms [32]. These particulate oxides are then effectively retained by membrane filtration processes, whether ultrafiltration (UF), nanofiltration (NF), or reverse osmosis (RO), which capture the oxidized metal particles and any associated metal ligand complexes. Finally, adsorption or ion-exchange units, either integrated with the membrane modules or employed as standalone polishing stages, remove any residual dissolved metal species [33]. By combining oxidation, membrane separation, and sorption or ion-exchange, these hybrid systems achieve higher selectivity for iron and manganese, reduce membrane fouling, and prolong overall membrane lifespan.

Several case studies have validated the effectiveness of these strategies: It is reported over 85% removal of Fe and Mn using polymeric UF membranes with pre-oxidation and pH adjustment in Malysia [34] and also it is developed PES membranes embedded with CuO nanoparticles, achieving high selectivity for Fe^{2+}/Mn^{2+} and improved anti-biofouling behavior [35].

Table 3: Comparison of Membrane Techniques for Fe/Mn Removal.

Membrane Type	Target Forms	Advantages	Limitations
MF / UF	Oxidized (Fe^{3+}, MnO_2)	Low cost, low pressure, good for particulates	Needs pre-oxidation; poor dissolved ion removal
NF	Fe^{2+}, Mn^{2+} (partially)	Moderate ion rejection, lower energy than RO	Not complete rejection; membrane fouling
RO	Fe^{2+}, Mn^{2+} (all forms)	High rejection, effective for dissolved ions	High pressure; prone to scaling; costly pretreatment
Modified PES/CS	Fe^{2+}, Mn^{2+}	Tailored selectivity, anti-fouling	Scalability and stability challenges

6 Polymeric membrane for brackish water treatment

Hydrophobic membranes

Hydrophobic membranes typically made from polymers such as PVDF (polyvinylidene fluoride), PTFE(polytetrafluoroethylene) and PP (polypropylene) play a key role in membrane distillation (MD) processes, where only water vapor is allowed to pass, leaving behind dissolved salts, heavy metals, and organic contaminants. In one study, a PVDF hollow-fiber membrane modified via plasma activation and silane grafting (contact angle > 112°) achieved over 99% salt rejection, while retaining steady water flux during fouling tests flux reduction was only 3–13%, compared to 65% decline in unmodified membranes [36].

Hydrophobic ceramic membranes coated with fluoroalkylsilane exhibited salt rejection >99% in desalination experiments, though permeability dropped significantly due to pore densification [37].

These membranes are especially effective at removing Salts (e.g., NaCl, TDS) via vapor-driven separation, Volatile organic compounds (vos) such as MTBE (methyl tert-butyl ether) through pervaporation using hollow fiber hydrophobic membranes (high mass transfer rates) [38] and even emerging organic micropollutants like pharmaceuticals (e.g., ciprofloxacin) with hydrophobic ceramic UF membranes modified by PDMS (polydimethylsiloxane), achieving >99% rejection at low concentrations (~1 mg/L) [39]. Nonetheless, hydrophobic membranes face notable challenges such as their inherent hydrophobicity makes them vulnerable to fouling especially by natural organic matter (NOM), biofilms, scale, colloids, and biofoulants which can decrease permeability and increase operational costs [40]. Porous hydrophobic structure may suffer wetting, leading to loss of selectivity and flux over time if contaminant deposition alters surface properties. To mitigate fouling, surface modifications like grafting hydrophilic or zwitterionic polymers, and incorporation of nanoparticles (e.g., Ag, TiO_2), are employed to enhance anti-fouling while maintaining hydrophobic vapor pathways [41].

Table 4: Summary of Hydrophobic Membrane Use in water Brackish Treatment.

Application	Pollutants Removed	Hydrophobic Membrane Type	Key Benefits	Challenges
Desalination via MD	NaCl, TDS	PVDF/PTFE hollow fiber	>99% salt rejection, low fouling decline	Wetting risk, reduced flux over time
VOC Removal (e.g. MTBE)	MTBE, volatile organics	PVDF hollow fiber pervaporation	Efficient mass transfer, high removal	Specialized design required
PPCP (pharmaceutical and personal care product) Removal (e.g. ciprofloxacin)	Pharmaceuticals	PDMS-coated ceramic UF	>99% micropollutant removal	Ceramic cost, pore blockage risks

Hydrophobic membranes offer a powerful tool for brackish water purification specially when targeting salts, volatile organic contaminants, or emerging micropollutants. Yet, achieving long-term performance requires careful design, surface treatment, and fouling management.

6.1 Hydrophilic membranes

Most membranes used for water treatment are initially hydrophobic (e.g., PES), but are modified to become hydrophilic to reduce biofouling and improve permeability. Hydrophilic membranes are widely used in the treatment of brackish groundwater due to their high-water affinity, reduced fouling potential, and selective removal of specific contaminants. Among the most commonly used hydrophilic polymers are polyethersulfone (PES), polyvinyl alcohol (PVA), cellulose acetate (CA), and polyacrylonitrile (PAN). These membranes are typically employed in ultrafiltration (UF) and nanofiltration (NF) processes, effectively targeting heavy metals, organic compounds, and particulate matter [42].

For example, PES ultrafiltration membranes embedded with CuO nanoparticles have demonstrated high removal efficiencies for iron (Fe^{2+}) and manganese (Mn^{2+}) ions from groundwater. In one study, a PES/CuO composite membrane achieved removal efficiencies exceeding 90% for Fe^{2+} and 85% for Mn^{2+}, while maintaining stable permeate flux and antifouling performance during long-term filtration tests [43].

Similarly, PVA membranes modified with chitosan have been reported to remove natural organic matter (NOM) and ammonia efficiently through adsorption–filtration coupling. These membranes exhibited more than 80% removal of NOM and 60–70% reduction of ammonia, depending on operating pH and dosage. In addition, cellulose acetate (CA) nanofiltration membranes have shown effective separation of nitrate (NO_3^-) and fluoride (F^-) ions from contaminated groundwater. One such study reported nitrate removal up to 96% and fluoride removal up to 92% at moderate pressure (2–4 bar) [44].

Table 5: Summary of Hydrophilic Membrane Use in water Brackish Treatment.

Hydrophilic Polymer	Process	Removed Pollutants	Removal Efficiency	Reference
CuO/PES	UF	Fe^{2+}, Mn^{2+}	Fe > 90%, Mn > 85%	Ahmed Abdel-Karim et al, 2022,Egypt. J. *Chem.*
Chitosan/PVA	UF/Adsorption	NOM, NH_3	NOM > 80%, $NH_3 \approx$ 70%	Hadi et al., 2021, Environ TechnolInnov
Cellulose Acetate	NF	Nitrate, Fluoride	NO_3^- > 96%, F^- > 92%	Sachin Karki et al., 2025, *Desalination*

6.2 Blended Membranes

Blended polymeric membranes have emerged as a promising approach in Brackishwater treatment due to their ability to combine the desirable properties of two or more polymers. By blending hydrophobic and hydrophilic polymers, or functional polymers with nanoparticles or biopolymers, these membranes offer enhanced mechanical strength, permeability, selectivity, and antifouling behavior. This makes them particularly effective in removing a wide range of pollutants from brackish water, including heavy metals, natural organic matter (NOM), ammonia, and pesticides [45].

For instance, a blended membrane of polyethersulfone (PES) and polyvinylpyrrolidone (PVP) has shown improved hydrophilicity and higher flux performance, facilitating the removal of Fe^{2+} and Mn^{2+} in ultrafiltration applications. In one study, PES/PVP membranes incorporated with TiO_2 nanoparticles removed over 90% of iron and 87% of manganese, while demonstrating reduced fouling and increased longevity [46].

Another example includes polyacrylonitrile (PAN) blended with sulfonated polymers, which has been used in nanofiltration to remove nitrate, arsenic, and agricultural contaminants. These blended membranes exhibited improved charge selectivity and stability across a broad pH range, achieving nitrate removal > 95% [47]. Blended membranes have also been tailored to remove emerging contaminants like pharmaceuticals and endocrine-disrupting compounds through the inclusion of functional additives such as graphene oxide or activated carbon, enhancing adsorption and rejection mechanisms during hybrid UF/RO processes [48].

They are made by physically mixing a base polymer with additives or secondary polymers before membrane casting to enhance performance (flux, antifouling, mechanical strength) and they used in UF/NF membranes for dissolved colloidal, heavy metals and suspended solid removal from brackish water.

- Common Blends for Brackish Water:
    - PEG /PES (Polyethylene glycol) – improves porosity and hydrophilicity.
    - Tween 20/PES or PVP (polyvinylpyrrolidone) – enhances hydrophilicity.
    - CuO or TiO_2 nanoparticles/PES antimicrobial and antifouling properties.
    - Chitosan /PES – for biofouling resistance and heavy metal binding.
    - PES/Polyaniline (PANI) – improves conductivity and heavy metal selectivity.

Table 6: Examples of Blended Membrane Applications.

Blended Polymers	Process	Removed Pollutants	Removal Efficiency	Reference
PES + PVP + TiO_2	UF	Fe^{2+}, Mn^{2+}	Fe > 90%, Mn > 87%	Ahmed et al., 2018, *J. Environ. Chem. Eng.*
PAN + sulfonated polymers	NF	Nitrate, Arsenic, Pesticides	NO_3^- > 95%, As > 90%	Zhao et al., 2020, *Water Research*
PES + PEG + GO	UF/NF	PPCPs, NOM	PPCP > 80%, NOM >	Li et al., 2021, *Membranes*

Blended Polymers	Process Removed Pollutants	Removal Efficiency	Reference
		85%	

6.3 Composite membranes

They are multilayered structures consisting of a thin selective layer (active layer) deposited on a porous support substrate. This configuration allows for the combination of high selectivity and mechanical stability, making composite membranes widely used in advanced water treatment applications, including reverse osmosis (RO), nanofiltration (NF), and forward osmosis (FO).

In brackish water treatment, composite membranes are particularly effective in removing inorganic contaminants such as iron (Fe^{2+}), manganese (Mn^{2+}), arsenic (As), and fluoride, as well as organic pollutants including natural organic matter (NOM) and emerging contaminants like pharmaceuticals and personal care products (PPCPs). The most common type is the Thin Film Composite (TFC) membrane, which features a polyamide active layer on a support of polysulfone (PSf) or polyethersulfone (PES).

In a previous study [51]. It was observed that fouling behavior in full-scale systems differed from bench-scale experiments, primarily due to variations in silica fouling on one side and the pre-oxidation of iron ions prior to testing on the other. These observations were used to propose membrane cleaning strategies, recommending that the cleaning process should initiate from the tail end of the bench-scale system. Despite differences in physicochemical conditions, fouling in both scales was found to be similarly reversible.
Another investigation [52]

explored the use of thin film composite (TFC) membranes for desalinating saline brackish groundwater in Egypt. The interfacial polymerization process employed conventional monomers meta-phenylenediamine (MPD) and trimesoyl chloride (TMC) at concentrations comparable to prior studies [53]. The optimal membrane performance was achieved using a formulation of 2.0 wt.% MPD and 0.5 wt.% TMC, with a 60-second reaction time followed by a 10-minute thermal curing step at 80 °C. This configuration resulted in 67% sodium chloride rejection and a water flux of 5.51 L/m²·h.

For example, a TFC-RO membrane was reported to remove over 97% of iron and manganese from brackish groundwater in a study by El-Bery et al. (2021, *Environmental Nanotechnology, Monitoring & Management*). Another study by Rana et al. (2018, *Desalination*) showed that TFC membranes modified with zinc oxide nanoparticles (ZnO NPs) exhibited enhanced antifouling properties and improved rejection of NOM and heavy metals, with rejection rates exceeding 90%.
Composite membranes can also be enhanced by nanomaterial incorporation, forming nanocomposite membranes that improve hydrophilicity, antibacterial activity, and permeability. For instance, incorporation of graphene oxide (GO) or silver nanoparticles (AgNPs) has shown to increase removal efficiency of PPCPs and microbial contaminants in hybrid RO/UF systems [54].

7 Challenges and Future Outlook

Despite their considerable potential for iron and manganese removal from brackish water, electrospun membranes face several challenges that must be addressed to realize their full-scale application. For instance, the incorporation of nanoparticles can lead to leaching, which necessitates surface immobilization or crosslinking strategies to secure these functional additives. Scalability remains an issue, but advances such as needleless or centrifugal electrospinning offer promising routes for mass production. The inherently low mechanical strength of nanofibrous mats can be mitigated by employing multilayer supports or composite architectures, while long-term stability in saline environments requires careful optimization of polymer matrices and additive combinations. Looking forward, research should prioritize pilot-scale demonstrations of electrospun modules treating brackish groundwater, explore hybrid configurations (e.g., coupling electrospun membranes with RO or UF systems) to enhance operational lifespan, and develop sustainable membrane platforms by integrating green polymers such as cellulose acetate, polylactic acid (PLA), or other biopolymers [55-56].

8 Conclusions

Brackish water, with its moderate salinity and complex contaminant profile particularly iron and manganese present unique challenges for sustainable treatment. Polymeric membranes have proven to be highly effective in addressing these challenges due to their tunable pore sizes, chemical resistance, and scalability. Among the different membrane types, reverse osmosis (RO) and nanofiltration (NF) are widely used for salinity reduction, while ultrafiltration (UF) and microfiltration (MF) have shown great promise in removing suspended solids and larger colloidal particles.

This review highlights the importance of selecting appropriate membrane materials based on water quality, target pollutants, and performance criteria. In particular, the incorporation of advanced techniques such as electrospinning has led to the development of nanofibrous membranes with enhanced permeability, selectivity, and antifouling resistance. These innovations not only improve treatment efficiency but also extend membrane lifespan and reduce operating costs.

Future research should focus on optimizing membrane formulations, integrating hybrid systems, and developing membranes tailored specifically for trace metal removal from brackish sources. With continued advancements, polymeric membrane technologies will remain at the forefront of safe, cost-effective, and environmentally friendly brackish water treatment solutions.

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