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Review

Advances in Produced Water Treatment Technologies: An In-Depth Exploration with an Emphasis on Membrane-Based Systems and Future Perspectives

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Abstract: This comprehensive review focuses on treatment technologies for produced water, with a particular emphasis on membrane-based systems. These systems offer significant advantages, including high contaminant removal efficiencies, compact design, and the potential for resource recovery. The review emphasizes the application of these technologies, their performance in meeting regulatory standards, and the challenges they face, such as operational efficiency and fouling. It highlights the need for further research and for the optimization of processes to enhance their efficiency. The integration of conventional methods with advanced treatment processes is also explored, with a vision toward developing hybrid systems for improved treatment efficiency. Overall, membrane-based systems show great promise for the treatment of produced water, but further advancements, sustainability considerations, and integration with other technologies are essential for their successful implementation in large-scale applications.

Keywords: produced water; membrane bioreactors; fouling; desalination; oil-water separation; electrodialysis

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1. Introduction

The petroleum industry generates approximately 250 million barrels per day of produced water, making it a substantial byproduct and the primary waste stream in terms of volume [1–3]. It is also referred to as formation water, which coexists with petroleum in the reservoirs of the Earth's crust. This water accumulates alongside hydrocarbons, as illustrated in Figure 1. Petroleum reservoirs can be categorized into conventional and unconventional types. Conventional reservoirs involve the entrapment of naturally occurring hydrocarbons such as natural gas and crude oil, by impermeable rock formations situated above them. Conversely, unconventional reservoirs are characterized by rocks possessing a low permeability and high porosity, which effectively confines the hydrocarbons in place and eliminates the need for a cap rock. The composition of produced water is indeed complex, consisting of various important components. These include oil in both dissolved and dispersed forms, organic and inorganic compounds, hydrocarbons, carbon dioxide, hydrogen sulfide, total dissolved solids (TDS), total suspended solids (TSS), inorganic salts, and heavy metals, among others [4]. Table 1 describes the quality of produced water based on reported studies. Hence, discharging untreated produced water into the environment can result in significant environmental impacts, affecting both human health and aquatic life.

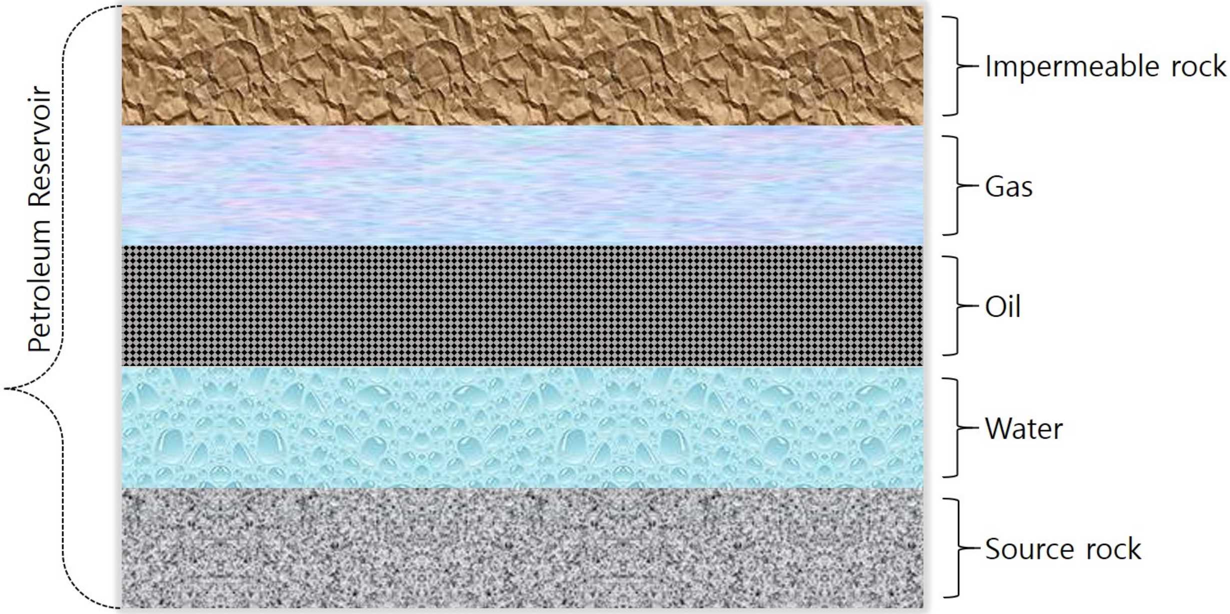

Figure 1. Schematic illustration of a representative reservoir.

The organic compounds present in produced water can cause harmful consequences, including increased resistance to biodegradation, carcinogenic properties, and high toxicity to marine life [5]. Exposure to these compounds can lead to various health issues such as tumors and cancer. Additionally, produced water can have endocrine-disrupting effects, affect non-endocrine systems, and impact the reproductive system [6,7]. It is crucial to properly treat and manage produced water to mitigate these environmental and health risks. Therefore, strict regulatory standards have been established to govern the discharge of produced water into the environment. Various technologies are employed to treat and purify produced water [8]. These technologies can be categorized into biological, chemical, and physical methods, including adsorption, microbial degradation, filtration, ion exchange, chemical oxidation, electrochemical oxidation, gas flotation, coagulation, photocatalysis, and membrane separation, among others [9–14].

The literature indicates that coalescence and destabilization mechanisms play a crucial role in achieving efficient oil-water separation, particularly for fine-sized oil droplets. Additionally, chemical demulsification has been recognized as a suitable and highly efficient method for oil-water separation operations [15]. Hydrocyclones have established their effectiveness in reducing the oil content present in produced water. However, they are often plagued by issues such as clogging and fouling [1]. Pressure-driven membrane-based processes have emerged as promising techniques for the treatment of produced water. However, membrane fouling represents a significant drawback associated with membrane-based processes, as it can progressively reduce their efficiency over time [16,17]. Additionally, the high energy costs associated with membrane operations are another limiting factor that needs to be addressed [2].

Table 1. Quality of produced water. The table is prepared based on data reported in earlier studies [18–20].

Parameters	Range	Unit
Conductivity	4200–58,600	(µS/cm)
pH	4.3–10	-
Density	1014–1140	(kg/m^3)
Turbidity	182	(NTU)
Surface Tension	43–78	(dyne/cm)
COD	1220	(mg/L)
TOC	0–1500	(mg/L)
TSS	1.2–1000	(mg/L)
Total oil	2–565	(mg/L)
Volatiles	0.39–35	(BTEX; mg/L)
Petroleum hydrocarbon (total)	>20	(TPH)
Non-volatile oil and grease (total)	275	(µg/L)
Bicarbonate	77–3990	(mg/L)
Chloride	80–200,000	(mg/L)
Sulfate	<2–1650	(mg/L)
Volatile fatty acids (VFA's)	2–4900	(mg/L)
Sodium	132–97,000	(mg/L)
Calcium	13–25,800	(mg/L)
Potassium	24–4300	(mg/L)
Lithium	3–50	(mg/L)
Iron	<0.1–100	(mg/L)

Membrane bioreactors (MBRs) have demonstrated an excellent treatment performance for removing both inorganic and organic components in comparison with physio-chemical processes and trickling filters. MBRs combine the biological treatment of wastewater with membrane filtration, resulting in enhanced removal efficiencies. The membrane barrier effectively separates suspended solids, microorganisms, and contaminants, resulting in higher treatment efficiency. This makes MBRs an attractive option for producing high-quality treated water, surpassing the performance of traditional physio-chemical processes and trickling filters [21–23]. However, it is worth noting that the majority of published reviews have focused on the generalized performance of MBRs for normal wastewater. In contrast, there has been relatively less attention given to the application of MBRs for the treatment of produced water [24].

The objective of this review is to provide an updated overview of the treatment systems employed for produced water, highlighting their advantages, disadvantages, limitations, and efficiency. Specific attention will be given to the application of these systems to different types of produced water. The review will also identify research gaps in the development of technologies for purifying oilfield-produced water. Furthermore, this article aims to assess the effectiveness and performance of membrane-based technologies, particularly membrane bioreactors and electrodialysis, for the treatment of produced water. By evaluating these membrane-based processes, their suitability and efficiency for produced water treatment will be estimated. Overall, this review seeks to offer valuable insights into the current state of produced water treatment systems, address research gaps, and evaluate the potential of membrane-based technologies for the purification of produced water.

2. Treatment Technologies for Produced Water

The primary objective of treating produced water is to address various aspects such as the removal of oil content (de-oiling), desalination, elimination of suspended particles and sand, removal of organic and inorganic components, elimination of dissolved gases, and extraction of heavy metals [25]. To achieve this objective, a range of treatment processes, including physical, chemical, biological, integrated, and membrane-based methods, are employed. Table 2 provides an overview of the different operations and technologies used in physical, chemical, biological, and membrane-based treatment processes. The table also highlights the effectiveness of these methods at removing specific constituents present in produced water.

2.1. Conventional Treatment Approaches

2.1.1. Adsorption

Adsorption is the most common water treatment technology [26]. The influential factors of adsorption are attached to the surface tension of solutions, temperature, nature, and quantity of the adsorbed substances [27]. Normally, no chemicals are required for adsorption [28]. Adsorption exhibits a remarkable efficiency of over 80% when employed to eliminate oil, total organic carbon, and heavy metals that are found within produced water [29]. Various materials, such as organoclays [30], zeolites [31], chitosan, and activated carbon [32], are used for adsorption. Numerous studies have provided evidence of the successful utilization of magnetic-based materials in the treatment of wastewater, showcasing their effectiveness at removing various contaminants such as heavy metals, organic pollutants, dyes, and pharmaceutical compounds [33,34].

Natural superwetting materials offer a promising solution for addressing the global issue of oil contamination due to their affordability, environmentally friendly properties, and widespread accessibility. Utilizing natural materials for oil-water separation holds great potential in tackling this challenge that has been widely recognized worldwide [35]. Coconut pith (CP), olive leaves powder (OLP), and eggplant peel powder (EPP) are utilized as adsorbents for the effective removal of oil and metals [36,37]. A study employed δ-Bi_2O_3 for the removal of bromide from aqueous solutions that contain low concentrations of chloride [38].

Akhlamadi et al. presented a sustainable solution for oil-water separation by introducing a superhydrophobic cellulose nanocrystal-based aerogel derived from waste tissue paper [39]. The aerogel exhibited a remarkable sorption capacity ranging from 69 g/g to 168 g/g for six different oils and eight organic solvents tested. In addition, the reusability experiments demonstrated that the aerogel maintained more than 92% of its sorption capacity even after undergoing 20 cycles of sorption squeezing. This indicates the excellent reusability and durability of the aerogel for oil-water separation applications. Azad et al. developed a hydrophobic and superoleophilic adsorbent by applying a coating of candle soot onto the surface of a recycled egg carton material [40]. The resultant carbon-coated adsorbent demonstrated an exceptional oil absorption capacity across a wide range of densities, eliminating the necessity for pre-treatments or surface modifications. The developed adsorbent exhibited successful absorption of various oils including diesel, engine oil, petrol, coconut oil, mustard oil, and refined oil. The adsorbent displayed a remarkable maximum absorption capacity of 3 g/g, indicating its high effectiveness in oil absorption.

Yu et al. utilized waste plastic to produce alveolate polystyrene (PS) foam [41]. The synthesis of the PS foam was achieved through a one-step process employing a high internal phase Pickering emulsion technique. The emulsion was effectively stabilized by a co-Pickering system comprising SiO_2 particles and Span 80 surfactant. The resulting SiO_2@PS foam displayed a unique multi-order pore structure and possessed superhydrophobic and superoleophilic properties. This made it highly effective at selectively removing various oily contaminants from water. The SiO_2@PS foam demonstrated an excellent adsorption capacity ranging from 20.4 g/g to 58.1 g/g (Figure 2), and it achieved rapid adsorption rates. One of the notable advantages of the SiO_2@PS foam was its reusability. After oil adsorption, the material could be easily reused through a simple centrifugation process. Even after 10 cycles, the decline in oil adsorption capacity was less than 1%, indicating its robust and durable performance. Overall, the SiO_2@PS foam developed by Yu et al. exhibited great potential for the treatment of oily water. Its superhydrophobic and superoleophilic properties, high adsorption capacity, and reusability make it a promising material for applications in oily water treatment and remediation.

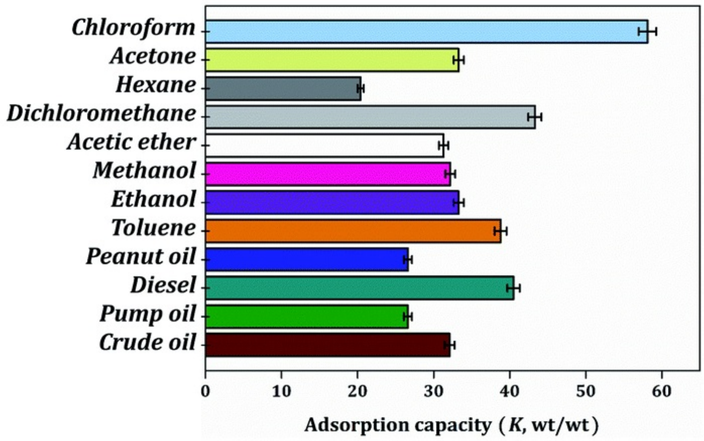

Figure 2. Different oil adsorption capacities of SiO_2@PS foam [41]. Image reused under the Creative Commons attribution license.

The performance of the adsorbent is influenced by temperature, pH, suspended solids, salts, and oils. The presence of suspended oil particles in produced water can lead to plugging of the medium and minimize the efficiency [42]. The usage rate of the adsorption medium directly impacts the operational cost of the adsorption treatment. During the replacement process of adsorption agents, disposal of solid waste becomes necessary [43,44]. Typically, this process is used in combination with other units, rather than alone. The combination of organoclays and activated carbon is efficient for the elimination of total petroleum hydrocarbons [45]. EARTH (Canada) Corporation has successfully developed a multistage process dedicated to the recovery of dispersed oil droplets found in produced water, specifically targeting those with a size greater than 2 microns [46]. The efficiency of adsorbents can vary under different conditions [27].

2.1.2. Cyclonic Separation

The cyclonic separation processes are also well-known in oil-water separation. A hydrocyclone is a device used to separate solid particles and/or immiscible liquids from a liquid, typically water. It is named hydrocyclone because the liquid (water) is considered the primary phase [47]. The principle of density difference between two liquids and/or a liquid and solid is employed in hydrocyclones. It is a physical technique where the strong rotational motion creates a radial acceleration, serving as the separating force. Hydrocyclones are constructed using metals, plastics, and other materials. They typically have a conical base and a cylindrical top, and their performance is intricately tied to the angle of the conical section [48]. The liquid stream is tangentially fed from the top, resulting in two discharge streams: one located at the top, known as the overflow or product stream, and another at the bottom referred to as the underflow or reject stream. The top stream is utilized for discharging the lighter phase of the input stream, while the bottom stream is used to discharge the heavier phase [49].

Produced water usually consists of oil droplets, surfactants, and suspended solids. Hydrocyclones, depending on the specific model used, are capable of removing particles within the size range of 5 to 15 µm. However, it should be noted that hydrocyclones are ineffective at removing soluble constituents present in produced water. Many companies utilize hydrocyclones for the treatment of produced water, with a capacity of treating approximately 8 million barrels per day [48]. Hydrocyclones operate without the need for any chemicals, making them highly efficient and cost effective. Additionally, they eliminate the necessity for any pre- or post-treatment steps, making the hydrocyclone the sole essential equipment for the treatment process. They are commonly employed as a pre-treatment step in conjunction with other technologies. Hydrocyclones have a long lifetime, low space requirements, small footprint, and do not need any additives [47,48]. However, they can experience significant pressure drops. The waste stream from the hydrocyclone (bottom output) consists of a concentrated slurry of solids that requires appropriate disposal measures [49]. This substantial production of concentrated solid slurry is a major drawback of this technique [48].

The efficiency of oil-water separation in hydrocyclones can be influenced by various factors, including processing capacity, the density difference between the two phases, geometry, temperature, pressure drop, and oil droplet size. Researchers have shown through their studies that separation efficiency ranges from 90.3 to 99.12% in the underflow, and the oil concentration in the overflow ranges from 77.8 to 98.82%, indicating a decrease in solid particle separation efficiency by 8.86% and an increase in oil droplet separation efficiency by 11.91% [50].

A recent study examined the effect of flow structures on the efficiency of hydrocyclones designed for oil-water separation, specifically focusing on single and dual inlets [51]. The study found that the use of a single inlet resulted in unsteady wavering flow, primarily caused by an imbalance in the flow immediately upon entering the cyclone. This unsteady flow adversely affected the separation efficiency, as it could transport water droplets located near the reverse flow core boundary into the overflow stream. Moreover, the presence of frequent recirculation zones led to the incomplete separation of fluid droplets. In contrast, the dual inlet hydrocyclone exhibited a uniform and steady fluid flow structure. This stable flow pattern facilitated the separation of oil and water into their respective core regions, with some inner cores rich in oil and some outer cores rich in water. The dual-inlet hydrocyclone demonstrated superior separation efficiency compared with the single-inlet hydrocyclone. At a 0.5 m^3/h flowrate, the dual inlet hydrocyclone achieved an efficiency of 82.3%, whereas the single inlet hydrocyclone achieved 73.7%. Figure 3 illustrates the oil superficial velocity vectors for both the single and dual inlet hydrocyclones. It focuses on the region starting from the inlet area and extending down to the tapering section, which is where the bulk of the separation process takes place [51]. The oil superficial velocity vectors provide a visual representation of the oil flow patterns within the hydrocyclones, offering insights into the fluid dynamics and separation efficiency of the two configurations. For higher flowrate (1.0 m^3/h), the dual inlet hydrocyclone demonstrated an excellent separation performance with an efficiency of 93.6%, while the single inlet hydrocyclone achieved a lower separation performance of 88.5% under the same feed conditions [51].

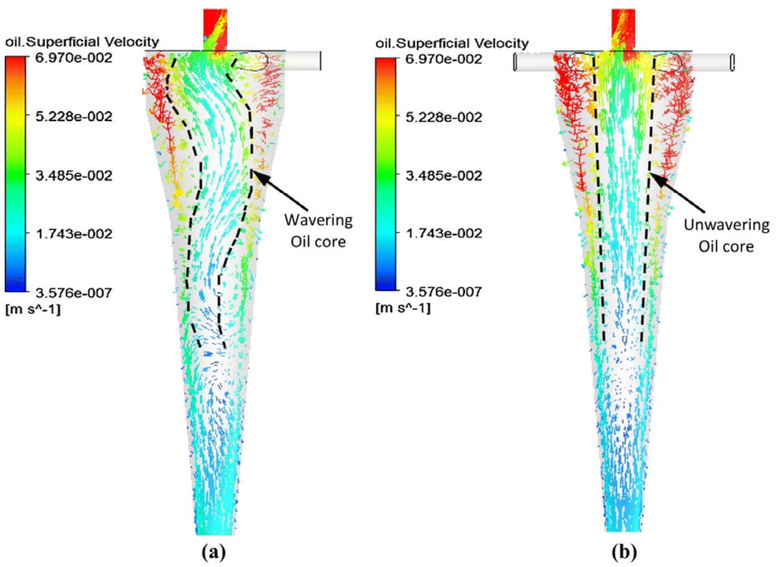

Figure 3. The oil superficial velocity vectors at a flowrate of 0.5 m^3/h flowrate were analyzed for a mixture consisting of 10% oil and 90% water in both the single (**a**) and dual (**b**) inlet hydrocyclone configurations [51]. Image reused under the Creative Commons attribution license.

This technology offers significant advantages and plays a crucial role in downhole oil-water separation. It reduces the cost of lifting produced water and helps control the moisture content of water. It is also employed to extend the exploitation of aging oil wells [48]. In the downhole oil-water separation process, the traditional liquid-liquid separation hydrocyclone (LLSH) is utilized in conjunction with screw pumps, causing the hydrocyclone to rotate around its axis. This rotational motion creates vortex systems within the fluid, where the outer vortex moves in the direction of underflow, whereas the inner vortex (reversed) moves in the direction of overflow. In the LLHC, the less-dense oil is directed towards the center of the device, while the denser water is forced to move towards the wall. As a result, water, with a higher water-to-oil ratio, exits the LLHC through the underflow outlet, while oil, with a higher oil-to-water ratio, exits through the overflow [52]. It is worth mentioning that the utilization of compact hydrocyclones with smaller and lighter specifications offers significant advantages in offshore environments, where space is limited. In offshore gas and petroleum industry applications, the capacity of the equipment can only be adjusted by blocking specific cyclone tubes within the equipment [53].

2.1.3. Sand Filtration

The removal and reduction of turbidity from water through filtration is a cost-effective and efficient process. Filtration involves the physical separation of dispersed compounds using a porous medium [54]. Sand filters are commonly recommended for water treatment while retaining organic matter [55–57]. These filters collect contaminants throughout the sand bed and effectively retain organic matter, making them superior to other filters [58]. As a result, sand filters have been extensively used in the treatment of residual water [59,60]. Cha et al. achieved reasonable outcomes in oil removal from produced water by employing a combined process of ozonation and filtration [61].

To effectively remove metals from produced water, several pre-treatment steps can be employed prior to sand filtration. These steps include adjusting the pH to initiate oxidation reactions, using an aerator to enhance O_2 concentration, employing a solid separation unit to allow sufficient retention period for the settling of precipitated solids, and employing sand filtration to remove fine solid particles that cannot settle effectively. Numerous systems have demonstrated over 90% removal efficiency for iron using this process [19]. While sand filters are commonly employed for metal removal from produced water [62], they are not typically utilized as a filtering medium for oil removal [61].

2.1.4. Dissolved Air Precipitation (DAP)

A study introduced DAP method to generate bubbles for solvent sublation bubble columns [63]. The solvent sublation process, introduced by Sebba in 1996, is a non-foaming bubble separation technique used for removing organic components from water [64]. This process involves applying high pressure, up to 820 kPa, to saturate the air in a packed column saturator. Afterward, the valve releases the pressure into the water column, causing the air to condense and create bubbles with a diameter ranging from 60 to 100 µm. This initiates flotation, leading to the separation of aromatic hydrocarbons and aliphatic compounds. At the pilot scale, the removal efficiencies for dissolved ethylbenzene, micro-dispersed decane, and dissolved octane were 40%, 75%, and 95%, respectively [63].

The influence of pressure on bubble size was significant at low salt concentrations but became insignificant at high salt concentrations. The removal of alkanes was faster compared with the aromatic compounds. The DAP/SS (dissolved air precipitation/solvent sublation) system was efficient at removing the total oil and grease (TOG) contents from produced water, achieving up to 70% removal efficiency [65].

Table 2. The known technologies and their applicability for produced water treatment [48,49,66].

Technology	**Desalting**	**De-Oiling**	**Softening (Mg and Ca Removal)**	**Removal of Suspending Particles**	**Iron Removal**	**Trace/Soluble Organics Removal**
Reverse osmosis (RO)	√	√	√	√	√	√
Nanofiltration (NF)	√	√	√	√	√	√
Ultrafiltration (UF)		√		√		√
Electrodialysis (ED)	√		√		√	
Thermal desalination	√		√	√		
Chemical treatment processes		√				√
Biological treatment processes						√
Activated carbon (AC)		√	√		√	√
Ion exchange process (IOP)			√		√	
Precipitation				√	√	
Aeration and sedimentation				√		
Deep bed filter		√		√		
API separator		√		√		
Hydrocyclone		√		√		

2.1.5. Gravity Separator/Coalescing Filter

Produced water, when treated using conventional gravity separation methods such as API separators, is often unsuitable for injection disposal or release into the environment. Gravity separation may not be efficient for heavy oil due to its similar density to water, requiring long detention times for effective treatment [67]. Therefore, alternative treatment methods, such as coalescence/filtration, are necessary to effectively treat produced water contaminated with oil.

In coalescence/filtration, which is a flexible method for accelerating the merging of small oil droplets into larger ones, water containing dispersed oil droplets in a hyper-saline continuous phase can be treated [68]. The coalescence process involves three steps: the droplets striking and adhering together, the coalescence of captured drops on the medium, and the growth of larger droplets that separate and settle. The key component of the coalescence/filtration process is the coalescing medium. Shirazi et al. conducted a study using a pilot plant (refer to Figure 3), to investigate the coalescence/filtration of wastewater contaminated with oil [69]. They used an electrospun nanofibrous filter made of polystyrene as the coalescing filtration medium and examined the influence of thermal treatment on the properties and efficiency of the filters. The thermally treated filters exhibited better efficiency for the separation of oil droplets, demonstrating the effectiveness of this process for separating oil from produced water streams.

Coalescers offer several advantages over other settling methods, such as gravity settlement. One notable advantage is their compact size, making them suitable for installations where space is limited. Additionally, coalescers demonstrate high separation accuracy, allowing them to effectively separate emulsified oil droplets that are smaller than 10 µm. This is a significant improvement over hydrocyclones, which struggle to separate such fine droplets [70]. The compact structure of coalescers contributes to their efficiency and effectiveness. They are designed for convenient operation and have a long service life for coalescence materials. Unlike other separation methods, coalescers do not require the use of additional reagents, making them cost-effective and environmentally friendly. As a result of these advantages, mechanical coalescers have gained widespread use in liquid-liquid separation processes. They have found applications in various industries where efficient separation of immiscible liquids is required, such as oil and gas, chemical, and wastewater treatment sectors.

Chen et al. analyzed the coalescing separator mechanism based on the principles of gravity separation, shallow pool theory, and equal flow theory [71]. They innovatively designed horizontal and vertical separators with different coalescing components, which were linked to make a multistage multiphase separation system (MMSS). Fluent computational fluid dynamics software was employed to study the flow field within the vertical separator. In their study, laboratory experiments were conducted to examine the influence of the flowrate, coalescing components, and parallel vertical separator on the separation efficiency of MMSS. The results demonstrated a significant improvement in separation efficiency compared with a one-stage horizontal separator. Four types of coalescing components, namely spiral tracks, semicircular baffles, 4-hole plates, and 7-hole plates, were tested to assess their impact on the separation of oil−water emulsions (Figure 4). It has been observed that the spiral track component is particularly suitable for handling small flow separation, whereas the orifice plate component demonstrates excellent performance in scenarios involving large flow separation.

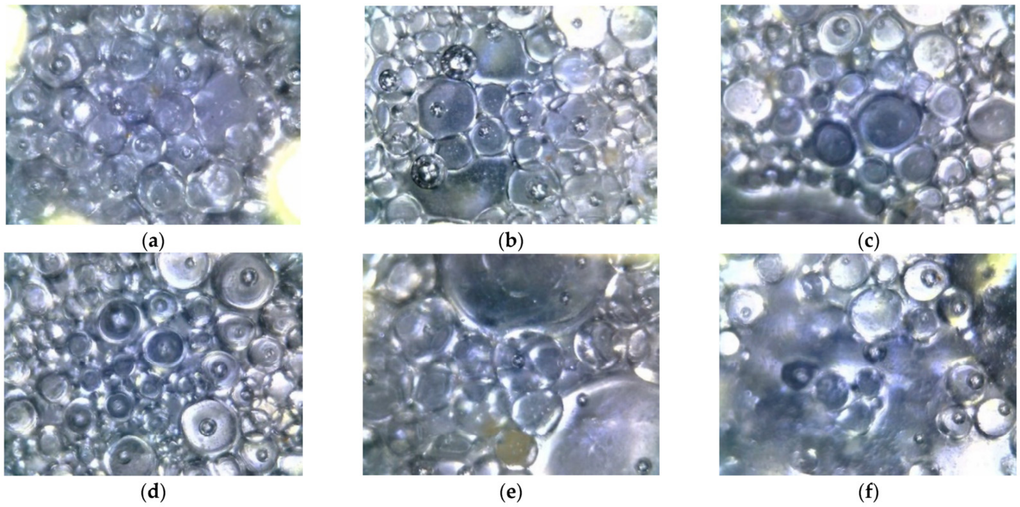

Figure 4. Morphological examination of the oil droplets at outlet of the vertical separator under various working conditions. The sub figures (**a**–**f**) signify a blank tube, semicircular baffle, spiral track, 4-hole plate, 7-hole plate, and all five risers are open, respectively [71]. Image reused under the Creative Commons attribution license.

2.2. Thermal Treatment Processes

2.2.1. Evaporation

The treatment of produced water using direct evaporation systems offers several advantages by eliminating the need for multiple chemical and physical treatment processes [25]. Various effective methods, such as vertical tubes, vapor compression evaporation, and falling film, have been employed for this purpose. The working principle of these techniques involves providing latent heat to the inlet water, causing it to evaporate and form vapor. The vapor is then condensed back into liquid water through cooling. This process allows for up to 98% recovery of produced water (high-quality distillate), with low levels of non-volatile inorganic TDS (<10 mg/L). The resulting distillate can be used as feedwater for Once Through Steam Generators (OTSG) or conventional boilers, improving their reliability and overall performance [72].

One of the significant advantages of direct evaporation systems is the elimination of physical separation and chemical treatment processes. This leads to reduced maintenance requirements, lower material and labor costs, and a decrease in de-oiling equipment for produced water. Additionally, the feed water quality for OTSG is improved, resulting in more efficient operation. However, direct evaporation systems have limitations related to the presence of an excessive concentration of solid salts in the produced water, which makes the reuse of concentrated salts unfeasible [73]. The energy requirements for these systems are also relatively high, leading to increased operating costs [74].

To optimize energy efficiency and minimize fouling, falling film vertical tube evaporators have been used. These evaporators have a high heat transfer coefficient and effectively remove oil contents from produced water. Prior to entering the evaporator, the produced water is preheated and deaerated to effectively remove non-condensed gases. The deaerated brine is then introduced into the evaporator, where it flows down the heat transfer tubes. As the process continues, a fraction of the brine evaporates, while the remaining liquid descends back into the sump for recirculation. Vapor condensation is achieved using a compressor [25].

Overall, direct evaporation systems offer a viable solution for produced water treatment, providing efficient separation and a high-quality distillate output. However, consideration should be given to the disposal of concentrated salts and the associated energy requirements.

Evaporation ponds, also known as solar evaporation ponds, are artificial ponds that are specifically designed to facilitate the efficient evaporation of water using solar energy [75]. These ponds serve various purposes, such as preventing the subsurface infiltration of water or controlling the downward movement of produced water. Evaporation ponds are often considered an economical option and have been widely utilized to treat produced water, both offsite and onsite [29]. They provide a natural and passive method for water treatment, relying on solar radiation and evaporation to remove water from the system while leaving behind concentrated contaminants.

In the operation of evaporation ponds, the produced water is directed into the pond, where it is allowed to disperse and cover a significant surface area. As the water is exposed to sunlight, and solar energy causes evaporation to occur. Over time, the water evaporates, leaving behind the concentrated contaminants, which can then be further managed or disposed of accordingly. Evaporation ponds offer several advantages, including simple process, low energy requirements, and cost effectiveness. They can be implemented in various locations and are particularly suitable for areas with abundant sunlight and available land.

However, it is important to consider the potential environmental impacts and ensure that the design and management of evaporation ponds comply with regulatory requirements to prevent any adverse effects on surrounding ecosystems or groundwater resources. Overall, evaporation ponds provide a practical and viable solution for the treatment of produced water, offering an efficient and environmentally friendly method for water management and disposal.

2.2.2. C-Tour

The C-Tour process is a method that employs solvent extraction principles to effectively remove residual hydrocarbons from produced water. The process involves injecting condensate into the produced water stream and allowing inline mixing to take place. By means of this mixing, the hydrocarbon impurities present in the produced water are extracted and combined with the injected condensate [76]. During the extraction process, the impurities and condensate coalesce, forming lighter and larger oil droplets. These oil droplets can be subsequently separated from the produced water stream using downstream treatment apparatus. The separation can be achieved through hydraulic or mechanical means, depending on the specific setup and system requirements. Once separated, the oil droplets are directed to the appropriate oil process streams for further treatment or utilization. This allows for the recovery and proper management of the hydrocarbons present in the produced water, reducing waste and potentially providing additional value.

The C-Tour process provides an efficient and effective solution for treating produced water while simultaneously recovering valuable hydrocarbons [76,77]. By employing solvent extraction principles and optimizing the mixing and separation steps, the C-Tour process facilitates the efficient extraction of hydrocarbon contaminants. This results in cleaner produced water and enhances water management in oil and gas operations as a whole.

The C-Tour technique has demonstrated its ability to effectively remove dispersed oil by 50 to 70% from produced water. Additionally, it has the capability to disperse dissolved organic material. Compared with other cleaning processes such as Epcon, C-Tour is more efficient at extracting PAHs (polycyclic aromatic hydrocarbons) and BTEX (benzene, toluene, ethylbenzene, and xylene), which are dissolved in water [78,79]. It has been found to increase the discharge of BTEX by 17% compared with other methods.

The performance of the C-Tour process can be influenced by the initial oil content present in the water and the percentage of NGL (natural gas liquids) injected [77]. A higher oil content has a greater effect on compounds within the C4–C5 range and phenols, while lower reference values also show an effect on PAHs (2–3 ring) and PAHs (4–6 ring). The impact of oil content increases with higher NGL injection rates. A pilot-scale study demonstrated promising results using real oil and real condensate in the C-Tour process. It achieved a remarkable 90% reduction in dispersed oil contents, indicating its effectiveness at removing oil from the produced water [76]. Furthermore, the C-Tour process has shown 90% removal efficiency for PHA compounds, highlighting the capability of C-Tour to target and extract specific contaminants from the water. These results from the pilot-scale plant validate the effectiveness of the C-Tour process at reducing dispersed oil and removing PHA compounds, indicating its potential for larger-scale implementation in oil and water treatment applications.

2.2.3. Freeze-Thaw Evaporation (FTE)

The FTE process is designed for managing produced water by utilizing natural temperature fluctuations. It involves freezing, thawing, and evaporation to generate a comparatively large volume of pure water suitable for various applications. In the FTE process, the produced water is initially preserved in a holding pond until the air temperature drops below 0 °C. Pumps are used to transfer the water from the pond, which is then sprayed onto a freezing pod. The freezing pod contains an elevated pipe grid with strategically placed sprinklers. The water undergoes freezing and thawing cycles within the pod. To remove the concentrated brine, the water is transferred to separate storage ponds [80,81].

During the winter season, the FTE process allows for the recovery of approximately 50% of the water, taking advantage of freezing and thawing mechanisms. However, in other seasons when freezing conditions are absent, the FTE operates similar to a traditional evaporation pond, and no water recovery occurs. The FTE process is highly efficient, achieving over 90% removal of total suspended solids, heavy metals, and hydrocarbons present in the produced water [81,82].

The FTE system has a lifespan of over 20 years and is designed for easy operation and monitoring [82]. It offers a chemical-free treatment approach, although its effectiveness relies on ample land space and specific climatic conditions. Proper waste disposal is an important aspect to consider when implementing FTE technology, as it produces a significant volume of concentrated brine and oil that require appropriate management strategies.

A study investigated the oil recovery from high-moisture oily sludge employing freeze−thaw and the solvent extraction process. Three solvents, namely CHX, MEK, and EA, were evaluated to determine the better solvent for oil recovery. The researchers found that by conducting a 30 min extraction at a solvent to sludge ratio of 4:1, approximately 40% of the oil could be recovered. Furthermore, more than 80% of the solvent used in the extraction process was successfully recycled. However, the recovered oil exhibited a relatively low total petroleum hydrocarbon (TPH) content, approximately 30% when using CHX and 40% when using MEK or EA. This lower TPH content was ascribed to the emulsified water present in the extracted oil. To address this issue, the researchers employed the freeze−thaw method, which improved the contents of TPH in the restored oil obtained from EA or MEK extraction. Specifically, the TPH content increased from

40 to 60% due to the dewatering effect achieved during the freeze−thaw process. Overall, the combination of freeze−thaw and solvent extraction techniques exhibited promising results in the recovery of oil from high-moisture oily sludge. This integrated approach has the potential to improve the TPH content in the recovered oil by effectively addressing the issue of emulsified water [83].

3. Advanced Thermal Separation Processes

Prior to the advent of membrane technology, thermal separation technologies were commonly utilized in large-scale desalination plants [48,84]. These technologies were employed in regions where the cost of energy for water treatment was comparatively affordable [84]. The primary thermal desalination technologies include vapor compression distillation (VCD), multistage flash (MSF) distillation, and multi-effect distillation (MED). MED-VCD plants are integrated thermal desalination facilities that aim to achieve a maximum performance [85]. Although membrane processes are generally favored over thermal approaches, recent advancements in thermal processes have made them more attractive for treating highly contaminated water, such as produced water [49].

3.1. Multi-Stage Flash (MSF) Distillation

MSF technology can indeed be employed for the desalination of various wastewaters, including produced water. Figure 5 illustrates the schematic of an MSF unit. The working principle of MSF involves reducing the pressure of the evaporation water rather than raising its temperature. The preheated feed water is introduced into a low-pressure chamber [86]. MSF technology is approximately 20% effective in terms of water recovery, and post-treatment is also required [86]. The system cost depends on many factors such as the site location, materials used for construction, type of feed water, size, and desalination capacity [87]. The energy consumption for the MSF process typically ranges from 3.35 to 4.70 kWh per barrel [88]. Moreover, MSF units have a lifespan of over 20 years [49].

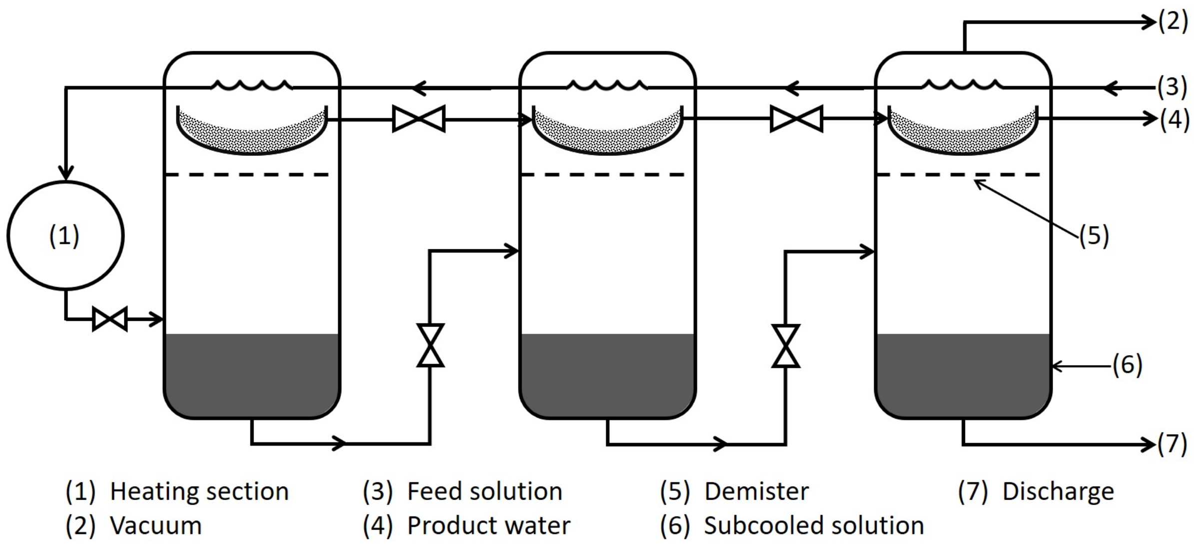

Figure 5. A schematic illustration of a three-stage MSF system to treat produced water.

A recent innovation introduced a system and method to process and recycle water utilized in an oil region steam operation [89]. A vaporizer-desalination unit was employed to separate a polluted water flow into two distinct streams: a flow designated for contaminated disposal and a separate flow consisting of clean water vapor. After the separation process, the polluted water flow is acquired by extracting it from the combined flow of oil and water originating from an oil well. Subsequently, the flow of clean water vapor is preferably routed via a steam generator to produce the steam required for the oil region steam operation. The generated steam is introduced into the oil region of a specified well, where it is utilized, and then retrieved as the combined flow of water and oil. Once adequately supplied by external water, the operational setup is structured to function continuously with minimal replenishment requirements, thanks to the effective water−vapor−steam cycle.

US11034605B2 introduced a new apparatus, system, and method for purifying produced water and removing valuable metals and minerals [90]. The apparatus comprises a device for flowing produced water from a wellbore to the produced water purification apparatus. It also includes at least one device for removing heavy metals from the produced water and at least one brine removal device for eliminating brine from the produced water. The method involves using the apparatus, and the system consists of a control panel that operates at least one device for removing heavy metals and at least one sensor in a coordinated manner. A series of connected sections can be created within the heat exchanger by engineering a combination of selected openings, baffles, perforated tubing, shunts, screens, and their combinations. This arrangement enables the operation of MSF systems. As the fluids pass through each section, gravity assists in the separation process, with the heavier liquids containing contaminants settling while the lighter vapor moves on to the subsequent section with reduced levels of contaminants. To enhance efficiency, the pressure can be lowered by incorporating a pump at the outlet located on the top of the heat exchanger. This adjustment facilitates the swift exit of purified vapor from the heat exchanger and lowers the boiling point of the fluid, further optimizing the overall performance [90].

3.2. Multi-Effect Distillation (MED)

MED technology is employed to improve efficiency and reduce energy consumption. This System involves the movement of feed water through a series of evaporators in which produced vapors evaporate water for the subsequent evaporator [91]. The produced water recovery rate can vary from 20 to 67% depending on the specific evaporator type employed. MED is particularly advantageous for treating produced water with a high TDS content [85]. These systems have a life cycle of 20 years and can be utilized for a wide range of influent qualities, such as MSF technology [88,91].

Li et al. evaluated the feasibility of MED process for treating high-salinity organic RO concentrates (ROCs) generated from wastewater treatment in the refining and chemical industries [92]. The experimental results revealed that approximately 6% of organic impurities volatilized (during processes of evaporation) and became part of the produced water, while around 8% entered the tail gas. Both the produced water and tail gas, which complied with relevant Chinese national standards, had the potential to be reused or directly released without requiring additional treatment. However, significant fouling issues occurred due to calcium sulfate when the water recovery reached approximately 30%, indicating the need to remove hardness from the ROCs prior to evaporation [92]. To further analyze the thermal and economic aspects of ROCs treatment, a forward flow MED model was developed using the Aspen Plus platform. A performance analysis was conducted, which involved studying the specific heat transfer area, fresh steam flow, and gained output ratio (GOR as functions of the heating steam temperature and effect number). The outcomes of study demonstrated that the efficiency of MED system was notably affected by the heating steam temperature and effect number. Enhancing the effect number in the MED system resulted in an improved thermodynamic performance. However, it should be noted that increasing the effect number also led to higher capital costs associated with the system [92].

Recent research demonstrated an impressive enhancement in produced water production through the utilization of MED modified with flash-box desalination. The study successfully generated 806 m^3/day of potable water, surpassing the output of conventional MED systems [93]. This achievement was made possible by reusing brines used as a secondary feed for the production of potable water.

3.3. Vapor Compression Distillation (VCD)

VCD is a unit equipped with a compressor that generates vapor extracted from the evaporator, and condenses it within a tube bundle. Various configurations of this unit have been developed to enhance heat exchange during the evaporation of saline water [86]. In recent years, mechanical vapor recompression (MVR) has been increasingly utilized for produced water treatment [94]. MVR technology offers several advantages over conventional VCD, including reduced system complexity and emissions from water streams. Moreover, the MVR process solely requires an electricity source to drive the system.

Figure 6 illustrates a flow diagram of the MVR process. To ensure optimal efficiency and prevent issues such as precipitation and corrosion on the plate heat exchangers, proper pre-treatment of the feed is necessary for the MVR system. The pre-treated produced water feed is subsequently pumped into the evaporator condenser, which is equipped with a vertical tube bundle. Within this configuration, the produced water undergoes evaporation, resulting in the production of steam.

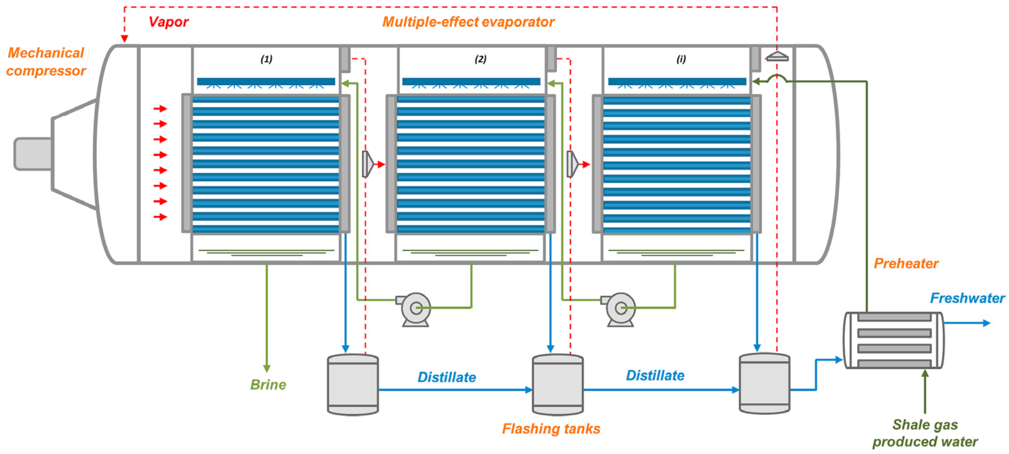

Figure 6. A schematic illustration of MVR system for the treatment of produced water [94]. Image reused under the Creative Commons attribution license.

3.4. MED–VCD Hybrid System

The hybrid MED−VCD process is a newly developed method specifically appropriate for produced water treatment [95]. It aims to enhance both energy efficiency and water recovery rates. By employing this process, significant improvements can be achieved by efficiently treating produced water from oil fields. This innovative technology is poised to replace the older MSF plants, as highlighted in the reported literature [95,96]. It offers distinct advantages over conventional produced water treatment methods. These benefits include reduced chemical dosage, lower overall costs, improved storage capabilities, mitigated fouling issues, easier handling, softer sludge generation, and more efficient management of waste streams [97]. Canada has already witnessed the installation of over 16 potable water evaporators, and the trend is expected to continue with the installation of more units in various regions across the globe [98].

ENTROPIE/SIDEM, a renowned company under Veolia (Aubervilliers, France), specializes in installing MED-VCD systems that guarantee high purity of treated potable water, with a claimed TDS level of <2 mg/L [95]. These systems allow for the direct utilization of the treated water in various industrial applications, with the option to use it either as is or after undergoing minor polishing if necessary. These applications cover a broad spectrum of industries, including the production of process water, boiler feed water, and water for closed-loop cooling systems.

The capital cost for the MED-VCD systems is estimated to be approximately $250 per barrel per day, as indicated in [48,87]. Conversely, the operational costs vary depending on the energy usage associated with the process.

4. Membrane-Based Treatment Systems for Produced Water

The membrane is a microscopic semipermeable material that separates substances of varying sizes by applying a driving force [99]. Membranes are typically composed of polymeric, ceramic, or metallic materials, which determine their properties, effectiveness, and performance in water purification processes [100]. Membranes can be categorized based on their pore size and particle rejection into four distinct types, including microfiltration (MF), UF, RO, and NF [101]. The pore size of MF membranes ranges from a few micrometers to 0.1 µm, UF membranes have pore sizes ranging from 0.1 to 0.01 µm, NF membranes have pore sizes ranging from 0.01 to 0.001 µm, and RO membranes have extremely small pore sizes ranging from 0.001 to 0.0001 µm [102]. Researchers have devoted significant efforts to improving the membrane performance through various approaches, such as material modifications and pore structure refinements [103,104]. Extensive work has already been completed, and ongoing research continues to explore new avenues for enhancing membrane efficiency [105].

Microfiltration and ultrafiltration are commonly used for removing oil from water. In the treatment of produced water, membrane technology can be employed for various purposes, ranging from minor treatment to the removal of suspended solids, oil, and desalination. Besides pressure-driven membrane systems (RO, NF, MF, and UF), the membrane bioreactor (MBR), which combines membrane filtration and biological processes, is another viable option for treating produced water. Membrane distillation, a membrane-based process, shows potential for the reuse of produced water [106]. Electrodialysis (ED) is another membrane-based desalination process [107]. The following membrane-based treatments are available for produced water, each with their own performance and efficiency characteristics.

4.1. Electrodialysis (ED)

The electrochemical separation process involves the ions being transported through an ion exchange membrane using a direct current voltage. This process is commonly employed for the desalination of wastewater. By applying a driving force, ionic substances from the source water move through the cathode and anode towards a concentrated waste water stream, resulting in the creation of a more dilute stream [108]. Dissolved solids in the produced water exist in the form of both anions and cations. These ions can be attracted towards electrodes that possess an opposing charge, as shown in Figure 7. Membranes are positioned between pairs of electrodes. Positively charged membranes selectively permit the passage of anions, while negatively charged membranes exclusively allow cations to pass through [29]. To facilitate the flow of feed water along the surface of each membrane, a spacer sheet is positioned between each pair of membranes [25].

According to Figure 7, positively charged ions such as sodium ions (Na^+) move towards the cathode, while negatively charged ions such as chloride ions (Cl^-) move towards the anode. Ions that have the same charge as the ion exchange membrane are rejected during this movement. Consequently, water undergoes concentration, resulting in desalted water being left behind in the neighboring compartment of the ED unit. In the subsequent section, both the desalted water and concentrate are continuously extracted from the unit. The principal unit of ED is a membrane stack consisting of several hundred cell pairs. These cell pairs are joined together with electrodes located on the outside. Prior to the ED process, pre-treatment of the water is essential to protect the membranes from potentially harmful substances, as the water passes through narrow passages. To transform alternating current (AC) into direct current (DC), a rectifier is employed.

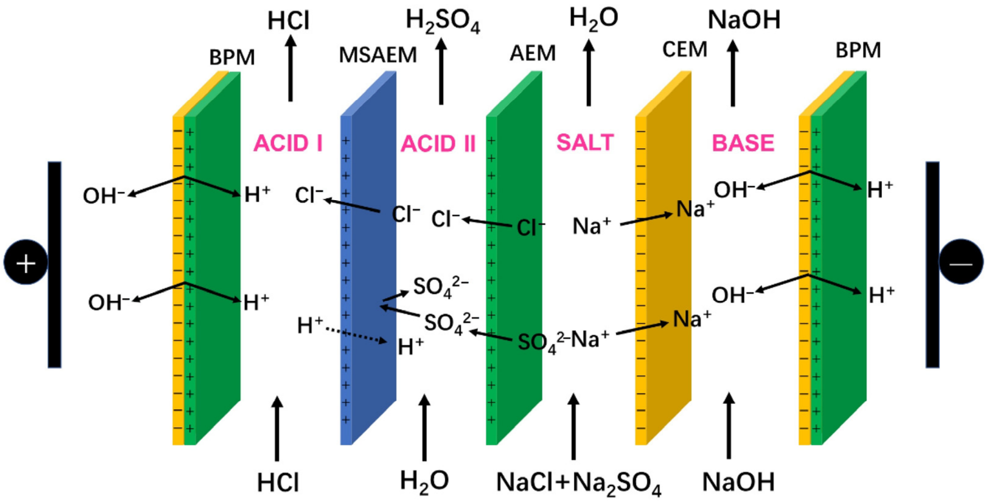

Figure 7. Schematic illustration of the innovative ED stack (SBMED) [109]. Image reused under the Creative Commons attribution license.

Post-treatment of the water involves stabilizing it and preparing it for distribution. This process may include the removal of gases such as hydrogen sulfide and adjusting the pH [25]. ED is a suitable method for treating low TDS concentrations, but it is typically not considered economical for treating concentrated produced waters due to various factors [110]. While ED is considered an outstanding technology for produced water treatment, particularly for relatively low saline-produced water, its application is currently limited to laboratory-scale experiments [111]. The life cycle of ED membranes is typically around four to five years. However, the main challenges associated with this technology include frequent membrane fouling and high treatment costs.

4.2. Membrane Bioreactors

The membrane bioreactor (MBR) is considered the best system for treating produced water due to its unique capabilities [24]. This process eliminates the need for a secondary clarifier, which is typically required in conventional activated sludge (CAS) treatment systems, as the membranes used in MBR serve as a means of solids separation [112,113]. Figure 8 visually compares MBR and CAS systems.

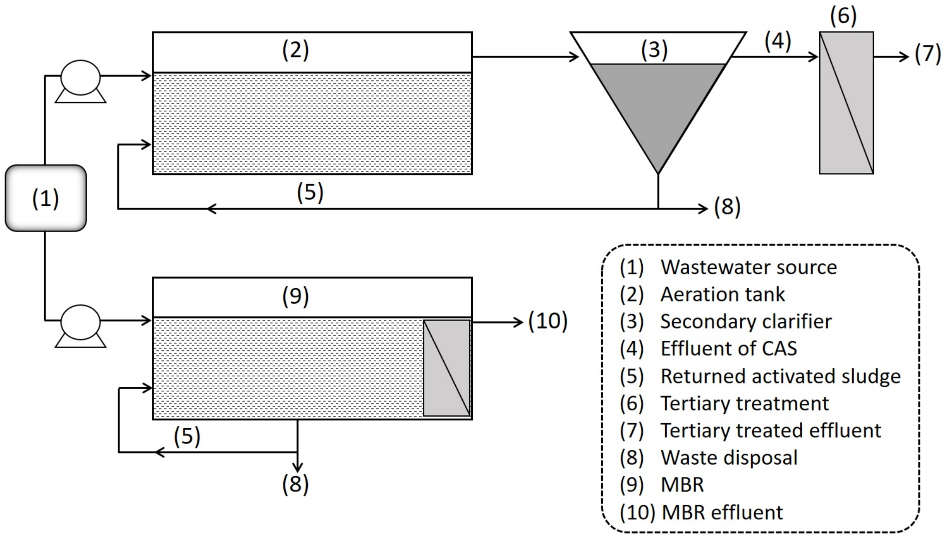

Figure 8. The schematic illustration of the conventional activated sludge (CAS) and MBR process.

MBR is a highly successful single system that integrates both physical and biological processes. In addition to integrating multiple processes, MBR technology offers several advantages, such as a simple control system, the ability to control the solid retention time (SRT), a reduced footprint, and ease of controlling the high retention time (HRT) [114]. The performance and purity of MBR systems depend on the pore size of the membranes. As the pore size decreases, the resistance to liquid flow increases, resulting in the need for higher operational pressures in the membrane system [102].

In a study conducted by Frank et al., a hybrid sequencing batch-reactor-MBR (SBR-MBR) process was employed for the treatment of both produced water and residential wastewater. The results demonstrated a remarkable reduction of over 90% in soluble chemical oxygen demand (COD) [115]. Two additional laboratory-scale studies conducted by Fakhru'l-Razi et al. [116] and Pendashteh et al. [117] showed impressive removal rates of 92% and 91% for TOC (total organic carbon) and TDS at concentration level of 16 g/L and 35 g/L, employing real and synthetic produced water, respectively.

In another study, a laboratory-scale MBR system was utilized to treat synthetic produced water with varying TDS levels. The results showed COD removal rates of 83% and 95% for synthetic produced water with TDS concentrations of 64.4 g/L and 144 g/L, respectively [118,119]. These studies highlight the effectiveness of MBR processes, both standalone and in hybrid systems, for the treatment of produced water, demonstrating significant reductions in various contaminants such as COD, TOC, and TDS.

A study was designed to evaluate the treatment of oil-field-produced water (OPW) using two submerged MBR setups, namely MBR-A and MBR-B [120]. Both systems operated using identical mixed liquor conditions, with pH 7 and 25 °C. The objective was to remove contaminants such as COD, oil and grease (O&G), and ammonia (NH_3) from the OPW. To maintain the desired dissolved oxygen (DO) content of approximately 3 mg/L, the air velocity in the systems was controlled using a rotameter set at 8 L/min. The results of the study indicate that both MBR-A and MBR-B achieved high removal efficiencies for COD, O&G, and NH_3, exceeding 90% under steady-state circumstances. Specifically, both MBR-A and MBR-B demonstrated an O&G removal efficiency of 96% [120].

While the MBR process has proven to be effective for treating high-strength wastewater [113], it is not without its challenges. Fouling and foaming are significant challenges associated with MBR systems [121]. The accumulation of solids and other substances on the surface of the membrane can lead to reduced filtration efficiency and hinder the overall performance of the MBR system [122]. This fouling phenomenon needs to be carefully managed to maintain optimal system operation and prevent any negative impacts on the quality of the effluent released into the environment [123].

The adverse impacts of fouling on both the efficiency of the MBR system and the effluent's quality, are significant concerns that should not be overlooked [124]. Membrane fouling can lead to decreased permeability, increased energy consumption, and reduced treatment efficiency [100]. Additionally, it can affect the removal of contaminants, including suspended solids, organic matter, and pathogens, potentially compromising the quality of the treated wastewater. It is important for operators and designers of MBR systems to implement strategies to mitigate fouling and foaming, such as proper membrane cleaning, optimized operating conditions, and the use of advanced monitoring and control techniques. Addressing these challenges is important to confirm the reliable and efficient operation of MBR systems and the production of high-quality effluent appropriate for environmental discharge or further reuse.

The cleaning of MBR systems is influenced by various factors, including operational conditions, the type and source of foulants, membrane material, and module configuration [100,125]. When it comes to cleaning methods, biochemical or biological cleaning is typically limited to in situ cleaning, meaning it takes place within the system itself. On the other hand, physical and chemical and cleaning approaches can be employed for both in-situ and ex situ cleaning, where the membranes are removed from the system for cleaning purposes. The selection criteria for the cleaning method highly depends on the specific circumstances and requirements of the MBR unit. Factors such as the composition and characteristics of the foulants, as well as the type of membrane used, play a crucial role in determining the most suitable cleaning approach. However, it is noteworthy that even with the application of physical, chemical, and biological cleaning methods, there may still be some instances where a portion of the fouling remains irrecoverable, especially in long-term operations. To optimize the cleaning effectiveness and minimize fouling-related issues in MBR systems, it is essential to implement a comprehensive cleaning strategy that combines appropriate cleaning methods, regular maintenance, and monitoring of system performance. This proactive approach can help maintain the long-term efficiency and reliability of the MBR system, while minimizing the impact of fouling on its operation.

5. Resource Recovery

Produced water is a complex mixture containing various valuable resources, including inorganic components, metals, crude oil, hydrocarbons, and water. The recovery of these resources, such as residual oil, hydrocarbons, and important inorganic components, can significantly offset the cost involved in produced water treatment and promote its reuse. Developing new techniques for resource recovery is essential in this regard [126].

One valuable metal present in produced water is lithium, which has significant applications in energy storage devices and electric vehicles to meet the growing demand [127,128]. The reclamation of produced water, particularly in enhancing oil production, involves a multistep process aimed at removing solids, oil, salts, and gases to ensure the water's quality for industrial, irrigation, livestock, and domestic use. The selection of suitable treatment technology for resource recovery depends on several factors such as treatment cost, the composition of produced water, environmental considerations, and water reuse standards. Figure 9 illustrates the treatment sequence for resource recovery and integrated treatment, which transforms produced water into a suitable resource for reuse by recovering oil and minerals, among other valuable components.

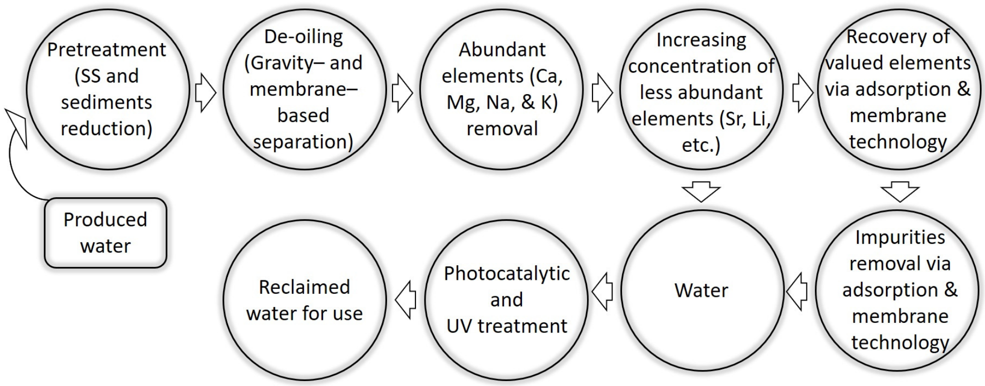

Figure 9. Flow diagram of the steps involved in resource recovery from produced water.

6. Future Perspectives

Produced water poses a significant challenge for countries involved in oil and gas production, considering that it constitutes the most substantial waste stream generated in the process. The production of each barrel of oil results in the generation of 3–10 barrels of produced water [19]. While approximately 95% of this water can be treated and reinjected to improve oil recovery, a substantial fraction remains. Unlike oil fields, water injection is not utilized in gas fields. As a result, oil and gas companies face the challenge of finding cost-effective and efficient treatment technologies to reduce contaminants in produced water for discharge or reuse purposes.

Because of the variations in the characteristics of produced water, such as differences between gas fields and oil fields, as well as variations among individual wells and based on good age, there is no universally recommended technique to meet entire environmental standards and recycling and reuse objectives [129]. The different methods discussed in this paper have their own advantages and disadvantages. The common shortcomings of physical methods include significant upfront investment and vulnerability to changes in water input. Chemical treatment, on the other hand, leads to the generation of hazardous sludge, which requires additional treatment and disposal efforts, along with major operational budgets and sensitivity to initial wastewater concentrations. Biological processes are sensitive to variations in organic substances and salt concentration in the incoming waste. These factors limit the feasibility of providing a single, overarching recommendation for the produced water treatment.

While there have been numerous studies examining the prospective reuse of treated produced water, government regulations pertaining to produced water reuse are currently limited [130]. Existing water regulations and guidelines primarily focus on water applications such as drinking water standards and irrigation guidelines set by organizations such as the Environmental Protection Agency (EPA), the United States, and the European Union water quality directive for groundwater (80/68/EEC) [129]. However, according to a recent research [131], more than 900 chemicals found in produced water do not have approved analytical procedures for the quantification or detection or in the regulatory framework established by the EPA. This implies that existing regulations may be insufficient to monitor the quality of treated produced water and ensure its safe reuse outside the oil and gas industry. To address this issue, it is advisable for regulatory bodies or organizations to establish comprehensive monitoring and assessment programs. These programs should thoroughly evaluate the potential effects and hazards associated with the reuse of reclaimed produced water, considering its impact on surface water, groundwater, ecological systems, and public health. It is important to conduct these evaluations prior to permitting the reuse of produced water outside the oil and gas industry. This would involve evaluating the effectiveness of treatment methods and implementing stringent monitoring protocols to ensure the safety of produced water reuse in other applications.

7. Conclusions

In conclusion, the produced water treatment is a critical challenge faced by the oil and gas industry. Various treatment technologies, including conventional approaches, thermal treatment processes, membrane-based systems, and resource recovery methods, have been explored. Each technology has its own advantages and limitations, making it crucial to select the most suitable approach based on the characteristics of the produced water and the desired treatment goals.

Among the technologies discussed, membrane-based systems, particularly electrodialysis and membrane bioreactors, demonstrate significant potential for efficient produced water treatment. These technologies offer high contaminant removal efficiencies, compact design, and the possibility of resource recovery, making them promising options for future implementation. However, further research is required to optimize the performance, cost effectiveness, and durability of membrane-based systems. Overcoming challenges related to fouling, membrane fouling, and operational costs will be critical to ensure the successful application of these technologies in large-scale produced water treatment.

Looking ahead, future efforts should focus on the development of hybrid treatment systems that combine multiple technologies, the integration of advanced treatment processes, and an increased emphasis on sustainability and resource management. By advancing treatment technologies and promoting responsible water management practices, the oil and gas industry can mitigate the environmental impact of produced water and contribute to a more sustainable energy sector.

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