

Next-Generation Technologies for Oilfield Produced Water Handling: Integrating Renewable Energy and Resource Optimization Towards Net Zero

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ABSTRACT

Oilfield produced water (PW), regarded as a wastewater of hybrid impurities, often contains challenging contaminants that defy traditional separation methods, including emulsified oils, surfactants, dissolved salts, heavy metals and even naturally occurring radioactive materials. Disposal methods such as sea disposal for offshore operations and deep-well injection for onshore operations raise environmental concerns including ecosystem distortion and induced seismic activities. As the industry strives for more sustainable practices, there is need for innovative separation technologies capable of efficiently removing these impurities and allow for extraction of valuable salts like lithium, magnesium, and bromine, as well as beneficial reuse of treated waters for irrigation in water-stressed regions, livestock water and industrial use thus promoting net-positive environmental impact and economic fortunes. This paper brings to fore next-generation membrane-based separation technologies designed for holistic treatment of produced water, including membrane distillation (MD), reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED) and filtration membranes, elucidating their separation principles, material advancements, separation performance, use of nanomaterials for performance enhancements, hybridization efforts, cost-benefit analysis as well as the future outlook for these emerging technologies. Also discussed in this paper are the potentials for promoting circularity in the oil and gas operations, through water re-use using energy efficient systems, brine mining to minimize waste disposal and open new economic opportunities. The paper also addresses the operational benefits, challenges, and scalability considerations for these next-generation technologies in produced water handling. From enhanced oil recovery and improved water quality to reduced environmental footprint and regulatory compliance, the potential impacts are far-reaching, contributing to both environmental stewardship and operational excellence. Through collaboration, research, and investment, the industry can propel forward towards a future where efficient produced water treatment is no longer a problem but a cornerstone of sustainable oil and gas production.

Keywords: Desalination Membranes; Beneficial Reuse; Circular Economy; Oilfield Produced Water; Mineral Recovery

INTRODUCTION

Produced water or oilfield produced water (PW) refers to wastewater generated during oil and gas production. Produced water (PW) can be categorized based on its origin into several types: oilfield PW, natural gas PW, coal bed methane PW, and shale gas PW [1,2]. The primary sources of PW include water injected into reservoirs for

enhanced oil recovery (EOR), flowback water from hydraulic fracturing, and formation or aquifer water naturally present within the reservoir [3]. These wastewaters often exhibit high salinity and organic contaminants [4], and can significantly impact the environment by polluting freshwater sources, disrupting aquatic ecosystems, and rendering agricultural land infertile when released untreated [5]. The U.S. Environmental Protection Agency (EPA) identifies saline and oily discharges as some of the most hazardous wastewaters due to high concentrations of persistent organic compounds, aromatic substances, heavy metals, and salts, which are challenging to treat [6]. Consequently, there is a critical need for cost-effective treatment methods to reduce the environmental impact of these saline and oily wastewaters, leading to the enforcement of strict discharge

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regulations. [7].

Handling of PW is typically via methods such as subsurface injection, transportation to offsite facilities, and application or discharge on land [8,9]. Traditional treatment methods include biological degradation, filtration, chemical separation, gas flotation, and thermal processing. Despite their effectiveness, these approaches often involve significant costs, the use of chemicals, and the risk of secondary pollution [10]. Also, with environmental regulations becoming increasingly strict, there is a pressing need to advance treatment technologies to meet current standards for safe discharge or reuse [11]. Oilfield produced water should not exceed 40 ppm of oil-water emulsion before being released into the environment. To enforce this, many countries have established stringent laws, regulations, and effluent limits for oil and gas companies [1]. As a result, oil companies worldwide are working to achieve zero-discharge goals.

In recent years, efforts to manage PW have evolved beyond traditional methods like deep-well injection and surface discharge, which carry risks of seismic activity and potential contamination of groundwater sources [12]. Instead, the focus has shifted towards innovative treatment technologies that not only mitigate the environmental risks associated with PW but also explore pathways for resource recovery and beneficial reuse. Advances in membrane-based separation technologies, such as membrane distillation (MD), reverse osmosis (RO), and forward osmosis (FO), offer promising solutions [13]. These technologies, often enhanced with nanomaterials and hybrid systems, aim to achieve high efficiency in contaminant removal, opening avenues for PW reuse in agriculture, industrial applications, and even renewable energy generation through salinity-gradient power [8].

This paper provides a review of next-generation technologies for PW management, emphasizing renewable energy integration, circular economy potential, and resource recovery, such as lithium extraction. Additionally, it examines the economic and regulatory implications associated with these emerging technologies. By assessing the latest developments in PW treatment, this review highlights the transformative potential of these technologies for sustainable oil and gas production, positioning PW not as waste but as a valuable resource for environmental and economic gain.

Produced Water and its Chemistry

The general categorization of PW constituents is the following: dispersed hydrocarbons, dissolved gases, dissolved organic and inorganic compounds, suspended solids and production chemicals [3]. So basically, these include salts (i.e. salinity or TDS), oil and grease (O&G), benzene, toluene, ethylbenzene and xylenes (BTEX), polyaromatic hydrocarbons (PAHs), phenols, organic

acids, calcium, magnesium, sulphates, barium, biocides and corrosion inhibitors. Table 4 present a summary of major PW constituents and their typical range of concentration in oil fields and gas fields.

Table 1: Typical PW constituents for oil fields [14,15].

Parameter	Oil field	Gas field
Total oil/grease	2 – 565	2.3 - 60
Total organic carbon (TOC)	500 - 2000	67 – 38,000
Total suspended solids (TSS)	1.2 – 1000	8 - 5484
Total dissolved solids (TDS)	247,000	2600 – 360,000
Chemical oxygen demand (COD)	1220	2600 – 120,000
Sodium	132 - 97000	520 – 120,000
Chloride	80 - 200000	1400 – 190,000
pH	4.3 – 10	3.1 – 7.0

Environmental Concerns from PW Management

Improper disposal of (PW) has severe environmental consequences, introducing various contaminants that can harm ecosystems and human health. BTEX compounds, a common group of pollutants in OPW, have been associated with numerous health issues, including skin disorders, neurological damage, blood disorders like aplastic anemia, and poisoning effects, often resulting in respiratory injuries and headaches [16]. Despite these risks, BTEX is often overlooked in marine pollution assessments due to its high volatility and rapid breakdown in seawater.

Among the contaminants of greater regulatory concern are polycyclic aromatic hydrocarbons (PAHs), which are heavily monitored due to their carcinogenic potential and associated health risks. PAHs can lead to DNA damage, oxidative stress, cardiac dysfunction, and developmental toxicity in aquatic life [17,18]. High-molecular-weight PAHs are particularly harmful to fish, where they disrupt genetic function, growth, reproduction, and can cause cancer [19]. Another concern is alkylphenols, including nonylphenol and octylphenol, known for their endocrine-disrupting effects. Even at trace levels, these compounds in PW can adversely affect vertebrates and marine organisms [20,21].

In addition to organic contaminants, PW contains toxic inorganic compounds such as naphthenic acids, which act as xenoestrogens and are especially hazardous to aquatic life and wildlife like birds when present in tailing pond waters [22,23]. Trace metals in PW also pose environmental risks, although they often dilute and break down in seawater, reducing their concentration and, thus,

potential toxicity [24]. Nonetheless, the high toxicity of PW's chemical constituents poses an acute threat to marine ecosystems, particularly when present in high concentrations [25]. Due to these risks and the large volumes of PW generated from drilling, countries are enforcing strict regulatory limits on discharge content, pushing oil companies to pursue zero-discharge practices to minimize environmental.

Recently, deep well disposals have been associated with inducing seismicity in the ground, with a potential to cause tremors, as seen in the sharp and noticeable rise in earthquakes in the central United States from 2008 to 2015. These was resultant of increases in the underground disposal of PW from the oil and gas industry [26]. Hence, there is the need to transform PW management to prioritize beneficial reuse in various sectors.

Produced Water Treatment

Primary PW treatment involves the use of gravity separator, otherwise known as skimmers, on onshore platforms to remove dissolved gases, larger dispersed oils and suspended solids. This primary treatment stage can reduce the dispersed oil content to between 50 - 200 ppm [27]. The secondary treatment stage involves further reduction of dispersed oil content by gas flotation technique which disperses gas bubbles in the water phase and their attachment to oil droplets [28]. Offshore platforms often have the flotation unit in either the dissolved gas flotation (DGF, where gas bubbles are generated by nucleation) or in induced gas flotation (IGF, where gas bubbles are generated by mechanical dispersion) and the process can effectively lower the concentration to below the discharge requirement limits [3].

Membrane technology has been put forward for effective treatment of PW with the capacity of reducing oil concentrations further below 5 ppm, following primary treatment [29,30]. These methods however either had fouling related issues or inability to efficiently remove salt ions, or both. Table 2 gives an overview of various methods used in the industry for treatment of PW as well as recent advancements.

Fig. 1 shows a typical offshore produced water treatment facility from the primary separation of phases to secondary and tertiary treatments aimed at reducing oil-in-water concentration and subsequent disposal to the sea or re-injection for use in EOR.

Circular Economy Perspectives

limitations in subsurface disposal options, and the potential for induced seismicity in some regions. In the U.S., estimates show that PW volumes from major shale oil and gas plays reached approximately 600 billion liters (160 billion gallons) in 2017, which is about 60% of a single day's freshwater usage across the country. In these areas, total irrigation demand was roughly five times the

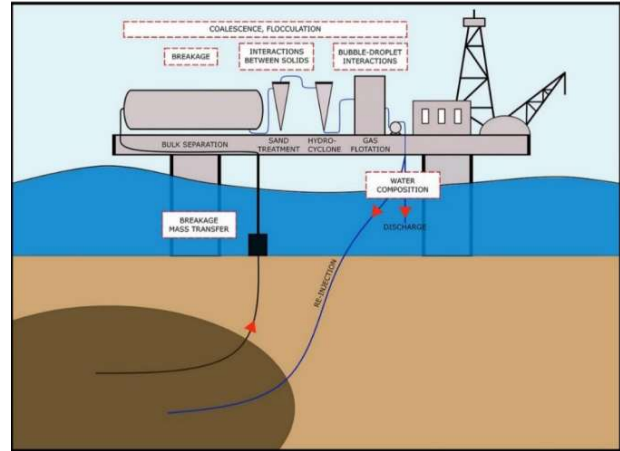


Figure 1: Schematic illustration of a typical offshore produced water treatment facility for re-use / disposal limits [3].

PW volume, while municipal water demand was about twice as much.

For hydraulic fracturing (HF) within the energy sector, reuse of PW is feasible in certain plays, where HF water demand often surpasses the PW volume, effectively eliminating excess PW in nearly half of these areas. However, PW quality, particularly its high salinity—such as in the Bakken play where median total dissolved solids reach around 255 g/L (seven times the salinity of seawater)—requires extensive treatment. In fact, treating PW from unconventional plays would likely reduce its usable volume by at least half. Desalination, for instance, would generate considerable salt concentrate, with the Permian Delaware Basin alone producing an equivalent of roughly 3,000 Olympic swimming pools of concentrate in 2017 [76].

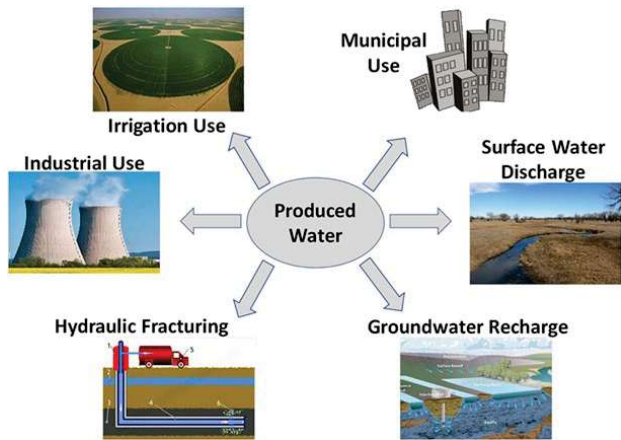


Figure 2: Beneficial use of produced water within the energy sector (hydraulic fracturing) and outside the energy sector (irrigation, municipal, industrial, livestock), surface water discharge (evaporation ponds, stream discharge) and groundwater recharge. [76]

Table 2: Summary of various methods for the treatment of PW

Conventional technologies					
Primary treatment	Method	Mechanism	Performance	Constraints	Ref.
	Gravity separators	Separation of components is based on gravitational force and differences in densities of the dispersed and continuous phases.	Primarily separates the oil, water and gas phases. The water phase still contains smaller dispersed and emulsified oils (up to 500 ppm) and other suspended and/or dissolved contaminants at this stage	Separators must be operated within specified limits. Oscillatory disturbances such as slug in-flow and sea waves could cause water continuous phase to pass such limits and enter oil continuous phase. Separation requires large equipment size for effective separation.	[31,32]
	Hydrocyclones	De-oiling is done by centrifugal force as fluid is fed under pressure through tangential inlet causing oil to migrate to the centre and pushing water to the wall in a vortex inner-outer flow regime.	It provides separation with higher efficiency than gravitational devices with shorter residence time while occupying smaller space. Oil concentration of 30 ppm in effluent is achievable.	Typically used on offshore platforms, efficient operation and control challenges still abound as models rely on empirical trial and error approaches.	[33,34]
	Coagulation and flocculation	A physico-chemical process that involves destabilization of the oil particles which are aggregated to form larger droplets and a flotation process to collect effluent.	Removal of total suspended solids (TSS) of up to 60 – 90% is achievable if a coagulant is used.	The efficiency with regards to removal of TOC is generally low.	[35]
		It is designed to remove suspended solids and colloids from waste streams.			
Secondary treatment	Gas floatation	Dispersed oil contents are further reduced by dispersing gas bubbles in water phase and their attachment to oil droplets to form lighter aggregates that can be skimmed from the top. It can be induced gas floatation or dissolved gas floatation depending on how the bubbles are generated.	This technique is capable of reducing oil concentration to levels below discharge limit, approximately 10 ppm. The floatation efficiency can be improved by a preceding coagulation-flocculation step.	It may not be cost effective to generate huge quantity of micro bubbles required for effective floatation.	[3,28]
Tertiary treatment	Walnut shell filtration	Filtration and backwashing are the two process cycles involved in nutshell filtration. Filtration involves trapping of oil and solids in the depth of the filter bed while backwashing involves scrubbing the filter bed of contaminant build up.	Oil concentration of below 5 ppm at the outlet is achievable with media filtration especially walnut shell filtration because of their superb oil and solids exclusion performance.	This treatment step is part of polishing done as final clean-up prior to disposal or re-injection. However, it is incapable of removing soluble hydrocarbon.	[28,36]
	Gas stripping	The process involves gas/liquid contact for volatile organic carbon (VOC) in PW to move to air in a contact tower at low pressures. Hydrogen sulphide (H ₂ S) is evaporated from solution and carried away in the gas effluent when natural gas or inert gas is used.	The simplest form of stripping involving sweet natural gas as stripper can reduce H ₂ S concentration to less than 30 ppm. Modifications have seen the removal of CO ₂ and BTEX compounds.	Stripping of acid gasses leading to rise in pH may lead to calcium carbonate scaling within the degasifier.	[37]
	Biological treatment	This technique is mainly dependent on aerobic pathway degradation where two main bacterial communities in the aeration tank are responsible for the treatment of wastewater. While the biological aerated filter (BAF) is dependent of fixed biomass, membrane bioreactor (MBR) and conventional activated sludge (CAS) depend on free moving biomass.	Aeration commonly used to supply oxygen for the process also causes the stripping VOCs (BTEX) present. CAS offers low cost and ease of operation whereas MBR is compact and offers better effluent quality.	There is the problem of inhibition of biological activity inside the bioreactor as a result of hyper salinity of PW. Also, the large footprint requirement of the CAS is a problem for offshore installation. Fouling of membrane in MBR has to be taken into consideration.	[38]
	Coalescing filters	This technique accelerates the merging of oil droplets in PW to form lesser but bigger droplets with wider diameter which trickle down or up in the medium and are separated. It is different from flocculation in that the droplets surface is ruptured and merges with other droplets to form a larger one.	It targets dispersed oil and PAHs	Even though coalescers are efficient, easy to maintain and can be used to separate unstable emulsion, there is need for periodic replacement of the filter beds when the concentration of solids in the effluent is high. Coalescence efficiency is also reduced with increasing oil concentration in the inlet.	[39,40]
Current/emerging methods					
Pressure driven membranes	Microfiltration (MF)	Exclusion of substances in the size range of 0.01 to 1.0 µm	Effective for removing micron-sized oil droplets with low operating pressures.	Membrane surface fouling when treating PW is still an issue. Dissolved salts are not removed.	[41–44]
	Nanofiltration (NF)	Combination of electrostatic attraction, Donnan exclusion/equilibrium and size exclusion depending on whether solutes are charged or not. Exclusion of substances in the size range of 0.01 to 0.001 µm.	Capable of removing sub-molecular organics and divalent ions.	NF has shown promise with high oil retention capacity; however, it has poor retention of monovalent ions like Cl ⁻ which are abundant in PW.	[41,42,45]
	Ultrafiltration (UF)	Exclusion of materials in the size range of 0.001 to 0.0001 µm.	It targets small suspended particles and dissolved oils; it is stable in high temperature and pressures.	UF membranes suffer from fouling and low flux and as such a shortened membrane life.	[42–44,46]
	Reverse Osmosis (RO)	Water is pushed through the semi-membrane in preference to solutes under pressure while rejecting dissolved salts into the brine stream in a continuous flow on the membrane surface. Exclusion of materials <0.0001 µm	RO can desalinate PW and remove last traces of dissolved and dispersed oil. It is also capable of removing various heavy metals in PW.	The main drawback of RO especially for treatment of hypersaline feeds like PW is build-up of osmotic pressure with increasing salt concentration in the feed which eventually exceeds the operating pressure of the system. It also requires pre-treatment steps to reduce the effect of membrane fouling and it is energy-intensive.	[42–44,47]
Low pressure membrane	Forward Osmosis (FO)	Separation is achieved via osmotic pressure difference between a draw solution and less concentrated contaminated feed solution. Water is selectively 'drawn' into the draw solution	FO can achieve high rejection of organic and inorganic contaminants in PW, effectively reducing the volumes of waste stream.	Membrane fouling is prominent which inhibits process performance and in turn affects flux. Chemically enhanced osmotic backwashing	[48–51]

		across the membrane in preference to contaminants in the feed.		removes salt scaling on membrane surface but only partially improves flux. Lack of efficient draw solution on the market is also an issue.	
Thermal processes	Brine concentrator and crystallizer	This technology is aimed at achieving zero-liquid discharges where highly concentrated brines are evaporated and crystallized into salts that can be of beneficial use. It functions via mechanical vapor compression (MVC) where evaporation of the mixture of feed water and brine slurry takes place in tubes of heat exchangers which vaporizes the slurry.	Brine concentrators can achieve results of solid concentration up to 250,000 ppm with up to 98% water recovery having less than 10 ppm TDS.	Extensive pre-treatment requirement in addition to high energy consumption makes the process costly.	[52,53]
	Multi-effect distillation (MED)	Evaporators are set-up in series and the feed is passed through them. Resultant vapor from one series evaporates water in the subsequent one. It is dependent on electrical and thermal energies.	Can be installed downstream of RO to further concentrate brine and is capable of water recovery up to 80%.	It requires pre-treatment of feed water to remove organics. Scaling may affect performance requiring cleaning. It also has higher energy consumption than RO.	[54–56]
	Electrodialysis (ED)	Charged compounds are targeted and removed in feedwater via an electrical potential difference-driven process across a membrane stack.	ED systems can operate at relatively higher concentrations of organic foulant in feed water than RO systems. Flushing allows for less dependence on pre-treatment chemicals.	The process is highly energy dependent and hence means more costs.	[57,58]
	Membrane distillation (MD)	Vapor generated from heating feed saline feed solution is selectively through hydrophobic membranes to condense on the reverse cold side as pure water.	MD is capable of 100% TDS removal at very low operating pressures while not being affected by osmotic pressure build-up, thus surpassing the drawbacks of RO.	Low surface energy organics in PW result in membrane surface fouling. Cheap alternative sources of thermal energy like solar and low-grade waste heat ought to be considered for economic viability.	[15,59–61]
Advanced/hybrid methods					
Dual and multi-component hybrids	UF-RO	In this array, organic molecules, bacteria suspended solids, etc. are removed by UF and salts are rejected by RO.	This array is capable of 100%, 98%, 98%, 95% and 100% reductions in oil and grease content, TOC, COD, TDS and turbidity, respectively.	Since RO is energy intensive, it potentially increases the overall cost of treatment making it not economically viable.	[62,63]
	NF-RO	NF targets sub-molecular organics and divalent ions while RO effectively removes monovalent ions.	NF can effectively remove multivalent ions that cause corrosion problems. Quality of permeate is recommended for livestock and crop watering.	It requires pre-treatment of feed to reduce the impact of fouling in addition to energy requirement of RO.	[64,65]
	MBR-NF-RO	Membrane Bioreactor (MBR) is used to pre-treat the feed before subsequent treatment with NF-RO system	MBR is capable of effectively reducing COD, TPI and O&G content in PW. NF and RO can achieve rejection of TPH of below 10 ppm in effluent and salt rejection up to 99%.	Multiple treatment steps may mean larger footprint and higher costs. Despite promising results, there is requirement for improvement of permeate	[66]
	FO-MD	FO is used to collect water across a membrane into the draw solution while MD produces clean water at the time recharging the draw solution	FO-MD has potential of 90% water recovery with almost complete oil and salt rejection.	flux and membrane fouling. Fouling of the FO membrane affects water flux.	[49,67–69]
	EC-FO-MD	In this setup, electrocoagulation reduces suspended solids and organics foulant in PW prior to feeding into FO-MD system.	Efficient removal of TOC, TSS and water recovery up to 78%, 96% and 76%, respectively in a prolonged operation.	Membrane modification required to overcome pore wetting with increasing draw solution concentration	[70]
Graphene membranes	Graphene oxide (GO), nano-porous graphene (NPG), graphene nanotubes	Incorporation of the carbon-based graphene nanomaterials into membrane matrix, onto membrane surface or freestanding membranes made of only graphene to improve performance of water separation is considered a game-changer for next generation membranes in desalination application.	Graphene nanomaterials cause reduced temperature polarization, selective sorption and nanocapillary effect greatly enhancing flux. Graphene nanomaterials have high rejection efficiency for multivalent metal cations, bacteria, COD and trace organic compounds.	Despite cheap cost of nanomaterial and tremendous potentials exhibited in performance improvement of desalination membrane, it is extremely tedious to construct high-density nanopores with controllable uniform sizes on graphene sheet.	[71–75]

Critical Mineral Extraction from PW

While lithium recovery from traditional sources like salt lakes and hard rock is well understood, interest is growing in extracting lithium from unconventional sources, such as oil and gas PW (OGPW). Studies indicate that lithium concentrations in PW can reach industrially viable levels in some areas. For instance, Marcellus shale PW has lithium concentrations ranging from 4 to 202 mg/L, while Smackover brines in the U.S. show even higher concentrations, exceeding 500 mg/L. With global PW volumes projected to reach between 499 and 3,585 million cubic meters, there is significant potential for lithium extraction from OGPW, which could help bridge the current supply-demand gap for lithium resources (Liu *et al.*, 2023).

With global lithium demands on the rise, direct lithium

extraction (DLE) methods are increasingly being explored as a viable approach to harness lithium from unconventional resources like PW, particularly where subsurface disposal is limited or where there is a high magnesium-to-lithium-ion ratio in the brine. These DLE technologies, Fig. 3, offer selective lithium recovery from complex brine mixtures, positioning PW as a potential asset in the global lithium supply chain [78].

Sorption Techniques

Sorption-based methods rely on specific sorbent such as aluminium, manganese, and titanium-based compounds—that selectively capture lithium ions from the brine. Manganese-based sorbents have shown high lithium affinity, especially suited for brines with complex ionic compositions. However, challenges such as sorbent

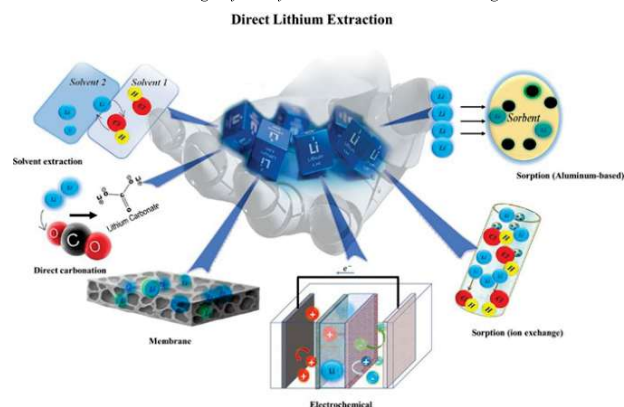


Figure 3: Various methods for direct lithium extraction from brines [77].

regeneration, particularly with acid-based desorption methods, and environmental impacts from the leaching of certain metals limit scalability for sorption techniques. Aluminum-based sorbents are more commercially viable due to lower costs and stable performance, although their lithium selectivity can be lower than that of titanium or manganese-based sorbents [77,79]

Solvent Extraction

Solvent extraction separates lithium ions from PW by utilizing organic solvents, which enable lithium recovery even in brines with high magnesium-to-lithium ratios. This method is relatively efficient; however, it presents environmental concerns, as the chemical solvents used can lead to waste disposal issues and may be cost-prohibitive. Despite the potential for high lithium selectivity, solvent extraction processes require careful management of chemical inputs to minimize environmental risks and ensure cost-effective lithium recovery [80,81].

Electrochemical Systems

Electrochemical extraction techniques apply controlled voltages to target lithium ions selectively, offering a clean extraction method without the use of hazardous chemicals. While promising in terms of lithium specificity and environmental sustainability, electrochemical methods are costly and limited by material availability and technological readiness for large-scale applications. These methods, though effective at pilot scales, require further development to overcome economic and operational barriers for commercial adoption [82].

Membrane-Based Processes

Membrane technologies, such as nanofiltration (NF), electrodialysis (ED), and advanced ion-selective membranes (ISMs), are among the most promising methods for lithium extraction from salt-lake brines [83]. ISMs, in particular, leverage nanofluidic channels that facilitate lithium-ion selectivity, providing high-purity lithium separation with minimal environmental impact.

These membranes are well-suited for DLE processes, especially as advancements continue in reducing costs and improving durability. Hybrid membrane technologies, including ion-imprinted membranes (IIM) and mixed-matrix membranes (MMM), combine sorption and separation mechanisms for lithium recovery, presenting an industrially feasible solution that maximizes selectivity and reusability [77]. Membrane-based DLE, especially ISMs, emerges as a promising approach due to its high scalability potential and lower environmental footprint, positioning it as a sustainable solution for lithium extraction from PW.

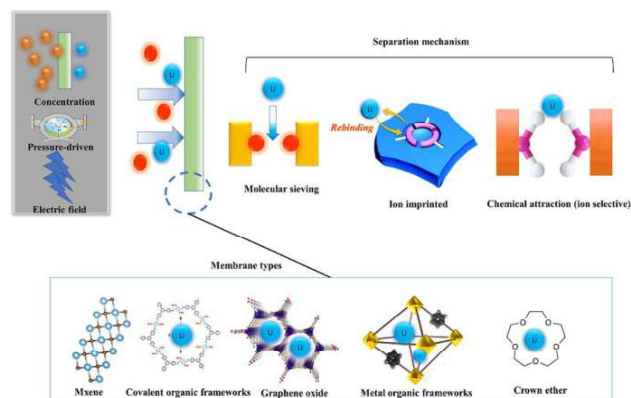


Figure 4: Separation mechanisms for membrane technologies application in metal recovery. Electrical potential, pressure, or concentration difference to transport ions through the membrane are the major driving principles. [77,81,84,85].

Other critical minerals recoverable from PW beyond lithium, include high concentrations of common table salts (sodium chloride) and magnesium salts, both of which have industrial and commercial applications. PW is also a potential source of rare earth elements (REEs), such as cerium, lanthanum, and neodymium, which are essential for various high-tech and renewable energy applications. The recovery of these minerals from PW not only presents an opportunity for resource sustainability but also aligns with waste-to-resource initiatives, turning a byproduct of oil and gas production into a valuable contributor to the circular economy [86,87].

RECOMMENDATIONS

To harness the economic potential of produced water (PW) management in Nigeria's oil and gas upstream sector, regulatory bodies and operators should focus on sustainable treatment and reuse strategies. The regulatory authority, Nigerian Upstream Petroleum Regulatory Commission (NUPRC), should establish stringent discharge standards for PW, ensuring minimal environmental impact. Additionally, the regulator should incentivize PW treatment and resource recovery, offering tax benefits or funding for technologies that enable lithium and other mineral extraction. By implementing

frameworks that facilitate the reuse of treated PW in industrial or agricultural applications, regulatory bodies can support a circular economy model in Nigeria.

Operators, on the other hand, should invest in advanced membrane-based and hybrid treatment technologies capable of extracting valuable minerals like lithium, magnesium, and bromine. Adoption of these technologies could position PW not only as a wastewater to be managed but as a resource with commercial value. Operators are encouraged to adopt "zero-discharge" goals, working with technology providers to scale direct lithium extraction (DLE) and other innovative PW reuse methods. By collaborating with local and international research institutions, Nigerian operators can enhance technical capacities, contributing to both environmental stewardship and economic investments.

CONCLUSIONS

Properly managed, produced water in Nigeria's oil and gas industry can transition from an environmental burden to an economic asset. Through stringent regulations, investment in technology, and collaboration among stakeholders, Nigeria can unlock the potential of PW, reducing environmental risks while creating revenue streams. By treating PW as a resource rather than waste, Nigeria's upstream sector can set a benchmark for sustainable practices in resource-rich countries, contributing to both environmental conservation and national economic growth.

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