ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

Lithium in North American Produced Waters: Geological Controls, Direct Extraction Mechanisms, and the Gap Between Synthetic and Real-Brine Evidence

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Publication Date: 2026/11/06

Abstract: Global lithium demand has increased rapidly, driven largely by expanding battery production, with consumption estimated at 263, 263,000 t in 2025. Supply remains concentrated among a limited number of hard- rock and salar producers. Oilfield- produced water in North America has emerged as a potential additional lithium source, particularly because oil and gas production already generates large volumes of this waste stream. This review synthesizes the geological, geochemical, and process literature on lithium-ion produced water from the Smackover, Haynesville, Bakken–Three Forks, Leduc, Wolfcamp, Eagle Ford, and Marcellus systems, and links basin-scale brine chemistry to the ion-selectivity mechanisms governing direct lithium extraction (DLE). Mean concentrations vary by approximately one order of magnitude across basins, from 16 mg/L in the Wolfcamp to more than 170 mg/L in the Smackover. Well- level concentrations in southern Arkansas range from 1 to 477 mg/L, reflecting evaporite dissolution, silicate water–rock interaction, and brine mixing rather than a general characteristic of oilfield water. Because Li^+ and Mg^{2+} have nearly identical ionic radii, Li/Mg selectivity in sorbent, solvent-extraction, and membrane systems arises primarily from the substantially greater hydration free energy of Mg2+. Most DLE performance data, however, are derived from synthetic or salar brines. The few tests conducted on actual oilfield or gas-field brines report results ranging from 77% single-stage extraction, with a Li/Mg separation factor of 5,737, to approximately 32% extraction when a system optimized for synthetic brine was applied to real, high-calcium brine. Geological characterization, process validation, and techno- economic assessment remain largely separate areas of research. We argue that integrating these fields through brine-specific testing, volume-weighted resource estimates, and transparent accounting for energy, water, and waste is the principal step required to scale lithium recovery from produced water.

Keywords: *Produced Water; Direct Lithium Extraction; Smackover Formation; Brine Geochemistry; Ion Selectivity; Critical Minerals.*

How to Cite: Raymond Aderoju; Mojibola Afolabi; Tracy Chukwuma; Olanrewaju Ayodele; Toheeb Hamzat; Ayodeji Aderibigbe; Olasunkanmi Olagboye (2026) Lithium in North American Produced Waters: Geological Controls, Direct Extraction Mechanisms, and the Gap Between Synthetic and Real-Brine Evidence. *International Journal of Innovative Science and Research Technology*, 11(10), 3093-3105. https://doi.org/10.38124/ijisrt/26oct1285

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

I. INTRODUCTION

Lithium demand, driven primarily by lithium-ion batteries for electric vehicles and grid storage, has grown rapidly. Global lithium consumption was estimated at 220,000 t in 2024 and 263,000 t in 2025, a 20% increase over one year (USGS, 2026). Conventional supply comes from two sources: hard rock spodumene deposits, dominated by Australia, and continental salar brines, concentrated in the Lithium Triangle of Argentina, Bolivia, and Chile (Kumar et al., 2019; USGS, 2026). This geographic concentration has prompted policies to diversify supply, including designating lithium as a critical mineral in the United States and the European Union's Critical Raw Materials Act (European Union, 2024).

Oilfield-produced water represents a fundamentally different lithium source from hard-rock ore or salar brine. Salar brines typically comprise Na–K–Li–Cl–SO_4–borate brines formed through the evaporative concentration of shallow groundwater in closed, arid basins. By contrast, oilfield formation water is more commonly a Na–Ca–Cl brine, with chemistry shaped by deep water–rock interactions, evaporite dissolution, and prolonged residence in hydrocarbon-bearing strata. Consequently, it contains higher concentrations of divalent cations and residual dissolved and dispersed organic matter (Ettehadi et al., 2024). This distinction is the primary reason that DLE technology developed for salar brines cannot be assumed to transfer directly to produced water, as discussed mechanistically in Section 6.

Historically, produced water has been water primarily as a disposal challenge, reinjecting it for enhanced oil recovery or into non-producing formations. Treatment and beneficial reuse remain relatively uncommon (Kaplan et al., 2017; Samuel et al., 2022). Recognizing that water from certain formations contains lithium concentrations comparable to those in commercially exploited brines has reframed produced water as a geologically heterogeneous resource: some formations are lithium-rich, while most are not (Dugamin et al., 2021; Knierim et al., 2024a; Marza et al., 2024).

Several reviews have covered parts of this topic. Kumar et al. (2019) argued for lithium recovery from oil-and-gas produced water; Ettehadi et al. (2024) reviewed geological controls in the United States; and Marza et al. (2024) examined geological controls on lithium ion basinal brines across North America. Gerardo and Song (2025) assessed resource quality and siting for lithium recovery from US oil-and-gas produced waters, and Karuppasamy et al. (2024) reviewed extraction technologies applied to oil-and-gas field produced waters. Reviews of DLE technology, in turn, focus mostly on salar and geothermal brines (Xu et al., 2016; Li et al., 2019; Battistel et al., 2020; Stringfellow and Dobson, 2021; Vera et al., 2023). To the best of our knowledge, no review grades process evidence by the type of brine on which it was measured. This review fills that gap by separating performance measured on real oilfield or gas-field brine from performance measured on synthetic or salar analogs, by weighting basin concentration by produced-water volume (Eq. 1), and by connecting basin geochemistry to the physical basis of DLE selectivity.

Figure 1 summarizes the resource pathway examined in this review. The review addresses three questions. First, what factors govern the occurrence and distribution of lithium ion-producing water across the major North American basins? Second, which direct lithium extraction (DLE) technologies have been tested on produced water or close analogs, what selectivity mechanisms do they employ, and what performance have they achieved? Third, where is the evidence connecting geological characterization, process validation, and economic and environmental outcomes weakest, and what research would address these gaps?

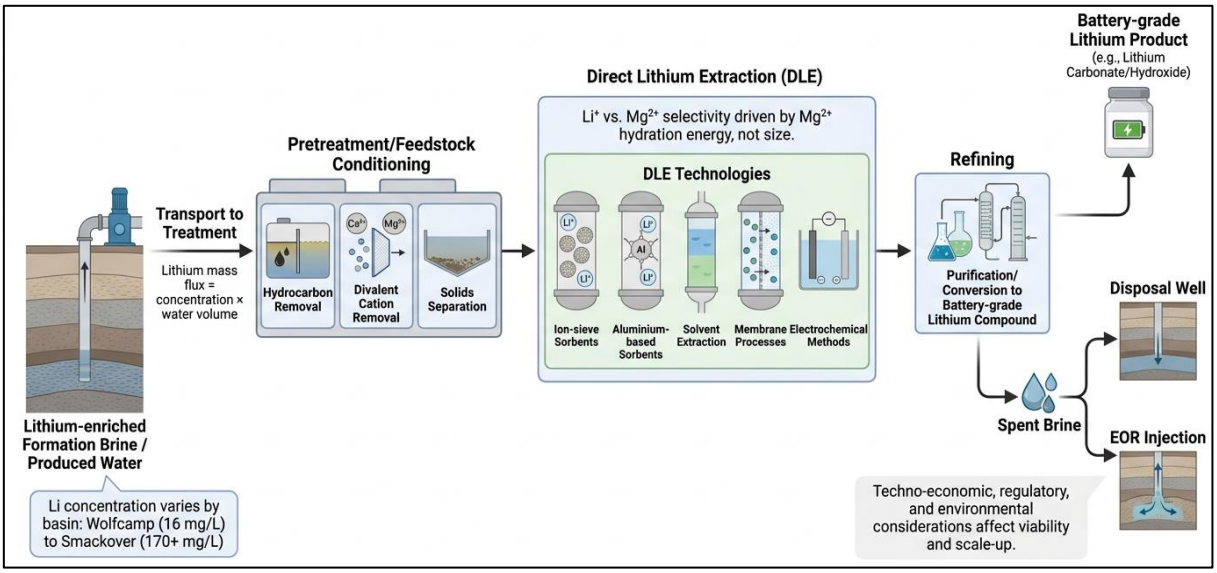


Fig 1 Resource Pathway from Lithium-Enriched Formation Brine to Battery-Grade Product. Mass Flux Depends on Both Concentration and Produced-Water Volume (Eq. 1). Spent Brine Returns to Disposal or Enhanced Oil Recovery (EOR) Injection.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

II. REVIEW METHODOLOGY AND SCOPE

A structured literature search forms the basis of this critical narrative review. We identified records published between 1970 and October 2026 in Scopus, Web of Science, and OnePetro, as well as publications from the USGS, the Alberta Geological Survey, and state geological surveys. Search strings combined resource-related terms ("produced water", "oilfield brine", "formation water", "flowback") with terms related to lithium and its recovery ("lithium", "direct lithium extraction", "ion sieve", "solvent extraction", "nanofiltration", "electrodialysis"). We also screened the reference lists of the retained studies to identify additional records. The review cites 49 sources in total. Studies were included if they reported measured lithium concentrations in formation or produced water from a named basin or formation, or reported lithium recovery from produced water, gas-field brine, or a synthetic brine explicitly designed to represent produced water. Studies of salar and geothermal systems were included when they established mechanisms or performance benchmarks necessary for comparison.

The geological scope is North American because basin-scale lithium data for produced water are most complete there. Non-North American oilfield and gas-field brines are cited when they provide the only available real-brine process data. Throughout, we distinguish three levels of process evidence: tests on real oilfield or gas-field brine, tests on synthetic brines designed to represent produced water, and tests on salar, geothermal, or generic synthetic brines.

➢ *Geological Occurrence, Genesis and Spatial Distribution*

Lithium enrichment in produced water is determined by basin-specific geological factors rather than by the co-production of water with hydrocarbons. The mean concentrations reported for the basins reviewed here vary by approximately an order of magnitude, while values from individual wells span more than two orders of magnitude (Table 1; Fig. 2).

- *U.S. Gulf Coast: The Smackover Formation*

The Smackover Formation is an Upper Jurassic carbonate system deposited along the margin of an evaporitic, restricted-marine basin associated with the opening of the Gulf of Mexico. It extends across the Gulf Coast from Texas through Louisiana, Arkansas, Mississippi, and Alabama to Florida. Across the Gulf Coast, the formation deepens from about 600m at its northern extent to more than 6,700 m farther south (Knierim et al., 2024b). Brine is hosted primarily in the upper, higher-porosity grainstone interval, informally known as the Reynolds oolite.

Regional water-chemistry studies indicate that Smackover brine composition reflects evaporite dissolution, water–rock interactions, and mixing among distinct brine bodies, rather than a single diagenetic process (Moldovanyi and Walter, 1992). Strontium isotope studies of the brines, their host evaporites, and carbonates indicate a history of dissolution and precipitation reactions with the enclosing rock, rather than simple entrapment of seawater (Stueber et al., 1984). Early work by the U.S. Bureau of Mines documented elevated concentrations of lithium, bromine, and iodine in Smackover brine associated with oil and gas production (Collins, 1974).

The most recent quantitative resource assessment employed a random forest model trained on historical (1965–2018) and newly collected (2022) brine analyses, alongside geological, reservoir, and temperature variables, to estimate lithium concentrations across southern Arkansas. Concentrations ranged from approximately 1 to 477 mg/L, with values exceeding 100 mg/L concentrated in Lafayette, Columbia, and Union counties. By combining predicted concentrations with reservoir porosity and thickness, the assessment estimated that the area contains 5.1 to 19 million tonnes of lithium in place, equivalent to 35–136% of the then-current U.S. lithium resource estimate (Knierim et al., 2024a). Lithium in place does not constitute a reserve; the recoverable fraction will depend on well productivity, brine recovery, and process efficiency.

- *Williston Basin (Bakken–Three Forks)*

Produced water from the Upper Devonian–Lower Mississippian Bakken–Three Forks petroleum system in the Williston Basin (North Dakota, Montana, and adjacent Canada) has been characterized in studies of brine origin and evolution. Lithium concentrations peaked at approximately 85 mg/L across 23 samples (Peterman et al., 2017). By comparison, the USGS National Produced Waters Geochemical Database reports a substantially lower average Bakken concentration of approximately 27 mg/L (Gerardo and Song, 2025). Accordingly, the 85 mg/L figure should be interpreted as the maximum observed among the 23 samples, rather than as a typical concentration.

- *Alberta Basin (Leduc and Devonian Carbonate Systems)*

The Upper Devonian (Frasnian) carbonate reef complexes of western Canada, particularly the Leduc Formation of the Woodbend Group, host a lithium-brine system with an enrichment mechanism distinct from that of the Smackover. The first systematic assessment of Alberta's formation-water industrial-mineral potential identified lithium concentrations up to 140 mg/L in Devonian carbonate buildups in the Fox Creek area of west-central Alberta. A subset of wells exceeded the detailed-exploration threshold of 75 mg/L (Hitchon et al., 1993; see also Eccles and Berhane, 2011). Recent isotopic research, combining 85 new and 57 historical analyses of oxygen, hydrogen, strontium, and lithium isotopes, found Leduc brine δ^7Li values of 14–16‰ (mean: 14.76‰). These values are distinctly lower than those of modern seawater and are consistent with lithium derived from silicate water–rock interaction with Cambrian–Precambrian metasediments and siliciclastic rocks, rather than from evaporite dissolution alone (Butler et al., 2025).

- *Permian Basin and other North American Systems*

Not all basins that produce large volumes of brine are lithium-rich. Produced water from the Wolfcamp in the Delaware and Midland sub-basins of the Permian Basin has total dissolved solids (TDS) concentrations ranging from below 20 g/L in low-salinity, clay-diagenesis-influenced basin-center wells to 140 g/L toward the basin margins.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

Across 268 samples, the oil-producing Wolfcamp interval averages only 16.2 mg/L lithium (Nicot et al., 2020, 2026). Produced water from the Eagle Ford in South Texas averages approximately 25 mg/L lithium; values exceeding 100 mg/L occur but are uncommon (Nicot et al., 2026). The Upper Jurassic Haynesville Shale of East Texas and northwest Louisiana, which lies stratigraphically above the Smackover, averages 71.7 mg/L lithium (range: 16–125 mg/L) at a mean TDS concentration of 126.7 g/L (range: 55–206 g/L). Its lithium isotope data indicate an enrichment pathway distinct from that of the Smackover, despite their stratigraphic proximity (Nicot et al., 2026). Produced water from the Middle Devonian Marcellus Shale of the Appalachian Basin, which is older than the Leduc, has been reported to contain an average of approximately 95 mg/L lithium (as summarized by Jang et al., 2017), and lithium mass yields from Marcellus produced water have been estimated directly (Mackey et al., 2024).

- *Concentration is Not the Resource: Volume-Weighted Lithium Flux*

Screening thresholds of approximately 65–100 mg/L are frequently cited for commercial applications (for example, Munk et al. (2016) report a minimum of 100 mg/L for economically viable brines, while Hitchon et al. (1993) use 75 mg/L as a threshold for detailed exploration); however, concentration alone does not determine resource significance. The annual lithium mass delivered by a produced-water stream is:

$$M_{Li} = C_{Li} \times V_{pw} \times 10^{-6} \quad (1)$$

Where M_{Li} is the lithium flux (t/yr), $C_{Li\ is}$ the lithium concentration (mg/L, numerically equal to g/m^3), and V_{pw} is the produced-water volume (m^3/yr). Every million cubic meters of Wolfcamp water at 16.2 mg/L therefore contains about 16 t of lithium, compared with about 175 t for Smackover brine at 175 mg/L (Table 1). Because the Permian Basin produces very large volumes of water (Scanlon et al., 2017), its total lithium flux may be substantial even though its concentration is low; whether that lithium is economically recoverable depends on process efficiency at low feed grade. Basin comparisons should therefore report both concentration and volume-weighted flux, as Mackey et al. (2024) did for the Marcellus.

Table 1 Reported Lithium Concentrations and Associated Controls in Produced Water and Formation Brine Across Major North American Systems. The "Li per 10^6 m³" Column Reports the Mass of Lithium Contained in One Million Cubic Meters of Produced Water at the Reported Concentration (Eq. 1).

Basin / formation	Age	Depth (m)	TDS (g/L)	Li (mg/L)	Li per 10^6 m^3 (t)	Main enrichment control	Key references
Smackover (southern Arkansas)	Upper Jurassic	600–6,700	NR	1–477 (wells); basin mean 174–187: add source	1–477	Evaporite dissolution, brine mixing, water–rock interaction	Knierim et al. (2024a); Moldovanyi and Walter (1992); Collins (1974)
Haynesville (E. Texas, NW Louisiana)	Upper Jurassic	NR	126.7 (55–206)	71.7 (16–125)	~72	Distinct from Smackover (Li isotopes)	Nicot et al. (2026)
Leduc, Fox Creek (Alberta)	Upper Devonian (Frasnian)	NR	NR	up to 140	up to ~140	Silicate water–rock interaction	Hitchon et al. (1993); Butler et al. (2025)
Marcellus (Appalachian Basin)	Middle Devonian	NR	NR	~95 (mean)	~95	Under investigation	Jang et al. (2017); Mackey et al. (2024)
Bakken–Three Forks (Williston Basin)	Upper Devonian–Lower Mississippian	NR	NR	≤85 (n = 23)	≤85	Not resolved	Peterman et al. (2017)
Eagle Ford (South Texas)	Upper Cretaceous	NR	NR	~25 (mean)	~25	Not resolved	Nicot et al. (2026)
Wolfcamp (Permian Basin)	Lower Permian	NR	<20–140	16.2 (mean, n = 268)	~16	Clay diagenesis and meteoric influence; low enrichment	Nicot et al. (2020, 2026)

NR = Not Reported in the Cited Sources.

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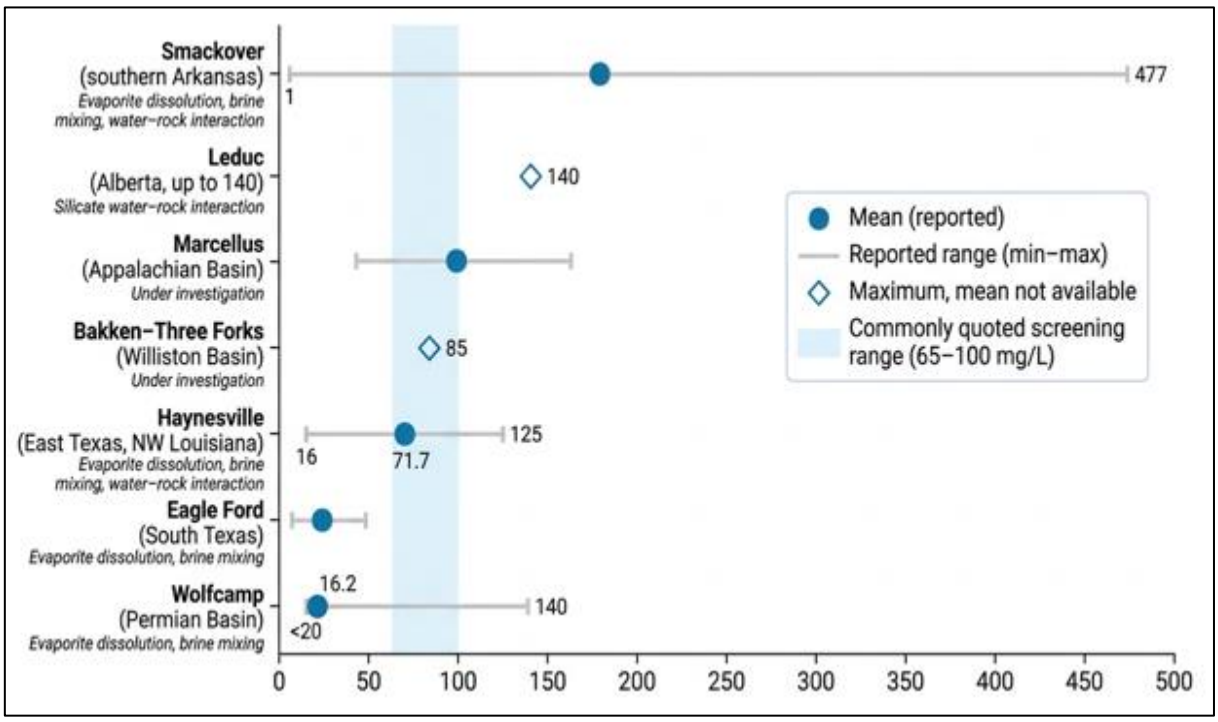


Fig 2 Reported lithium concentrations in produced water and formation brine from major North American systems, plotted using the values presented in Table 1. Points indicate reported means, bars indicate reported ranges, and open diamonds indicate reported maxima when no mean is available. These values are drawn from different studies and sampling programs and are not directly comparable. The shaded band denotes a commonly cited screening range.

➢ *Brine Thermodynamics at High Ionic Strength*

Smackover-type formation brines have ionic strengths substantially exceeding 3 mol/kg, where the extended Debye–Hückel and Davies equations no longer accurately characterize ion activities because they do not account for specific short-range ion–ion interactions. The Pitzer ion-interaction model was developed to describe such concentrated electrolytes (Pitzer, 1973; Pitzer and Kim, 1974) and was subsequently extended by Harvie et al. (1984) to the Na–K–Mg–Ca–H–Cl–SO_4–OH–HCO_3–CO_3–CO_2–H_2O system relevant to natural brines. In this formulation, the activity coefficient of a cation M is:

$$\ln \gamma_M = z_M^2 F + \Sigma_a m_a (2B_{Ma} + ZC_{Ma}) + \Sigma_c m_c (2\Phi_{Mc} + \Sigma_a m_a \psi_{Mca}) + \Sigma_{a,a'} m_a m_{a'} \psi_{aa'M} + |z_M| \Sigma_c \Sigma_a m_c m_a C_{ca} \quad (2)$$

Where F is a Debye–Hückel-type term that also includes derivatives of the second virial coefficients; m_a and m_c are the anion and cation molalities; B and C are binary cation–anion parameters; $Z = \Sigma m_i|z_i|$; Φ and ψ are mixing parameters for like-charged ion pairs and triplets; and the final two terms account for anion–anion–cation mixing and the ternary C parameter (Harvie et al., 1984).

Interaction parameters for the Li–Na–K–Ca–Mg–Cl system are available; however, we found no study that applies the model to the full major-ion compositions of Smackover, Leduc, Bakken, or Wolfcamp brines to predict lithium activity and extraction equilibria. Such calculations would transform the qualitative selectivity argument in Section 6.1 into quantitative, brine-specific predictions. We identify this as a research priority in Section 8.

III. PRETREATMENT AND FEEDSTOCK CONDITIONING

Produced water cannot be introduced directly into most DLE processes. Residual hydrocarbons, elevated divalent-cation concentrations, and suspended solids each impede downstream separation through distinct mechanisms. Accordingly, pretreatment design must address all three factors rather than treating them as a single purification step.

➢ *Hydrocarbon Removal*

Dispersed and dissolved hydrocarbons can foul membranes, degrade solvent-extraction systems, and block active sites on inorganic sorbents. Conventional treatment methods include gravity separation and skimming for free and dispersed oil; induced- or dissolved-air flotation for finer droplets; and adsorption using activated carbon or organoclay to remove dissolved organics. Ceramic microfiltration and ultrafiltration can achieve lower residual oil-in-water concentrations with a smaller footprint; however, they entail higher capital costs and are susceptible to fouling by the same hydrocarbons they are designed to remove (Samuel et al., 2022).

➢ *Descaling and Attenuation of Divalent Cations*

Calcium and magnesium are present in oilfield-produced water at concentrations substantially higher than those of lithium, reflecting water–rock interactions with carbonate and evaporite strata. In Bakken and Wolfcamp produced water, magnesium concentrations are 40 to 100 times higher than lithium concentrations, while calcium

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

concentrations exceed them by more than 400 times (Gerardo and Song, 2025). Chemical softening with soda ash or lime is the most widely used approach because of its low capital cost; however, it generates solid residues and removes some lithium through co-precipitation or entrainment. In synthetic shale-gas produced water, sodium carbonate precipitation removed more than 96% of barium, calcium, and strontium before lithium adsorption (Jang and Chung, 2018). Nanofiltration softening avoids solid-waste generation but is susceptible to scaling caused by the concentrated divalent ions it rejects. Lithium losses during softening are rarely quantified; therefore, each pretreatment study should report them, as these losses reduce overall flowsheet recovery.

➢ *Effects of Residual Organic Compounds on Downstream Separation*

Dissolved organic compounds that pass through pretreatment affect each DLE family differently. In membrane processes, they cause fouling, reduce the active area, and, in some cases, irreversibly block pores. In sorbent processes, they compete with lithium for active sites. For example, in synthetic shale-gas produced water, added organic compounds reduced the Langmuir maximum capacity of an H_2TiO_3 sorbent (Jang and Chung, 2019). In solvent extraction, organic compounds can partition into the organic phase and alter extraction behavior. Alkanes added to simulated shale-gas produced water reduced overall lithium recovery, with longer chains and higher concentrations causing greater reductions (Lee and Chung, 2020). Comparable effects have been reported for organophosphorus systems applied to real oilfield brine (Wu et al., 2025).

IV. MECHANISMS OF DIRECT LITHIUM EXTRACTION

This section examines the five DLE families relevant to produced water (Fig. 3): ion-sieve sorbents, aluminum-based sorbents, solvent extraction, membrane processes, and electrochemical methods. We discuss selectivity in terms of ionic radius, hydration thermodynamics, and host-lattice energetics, rather than treating each technology as a single performance metric.

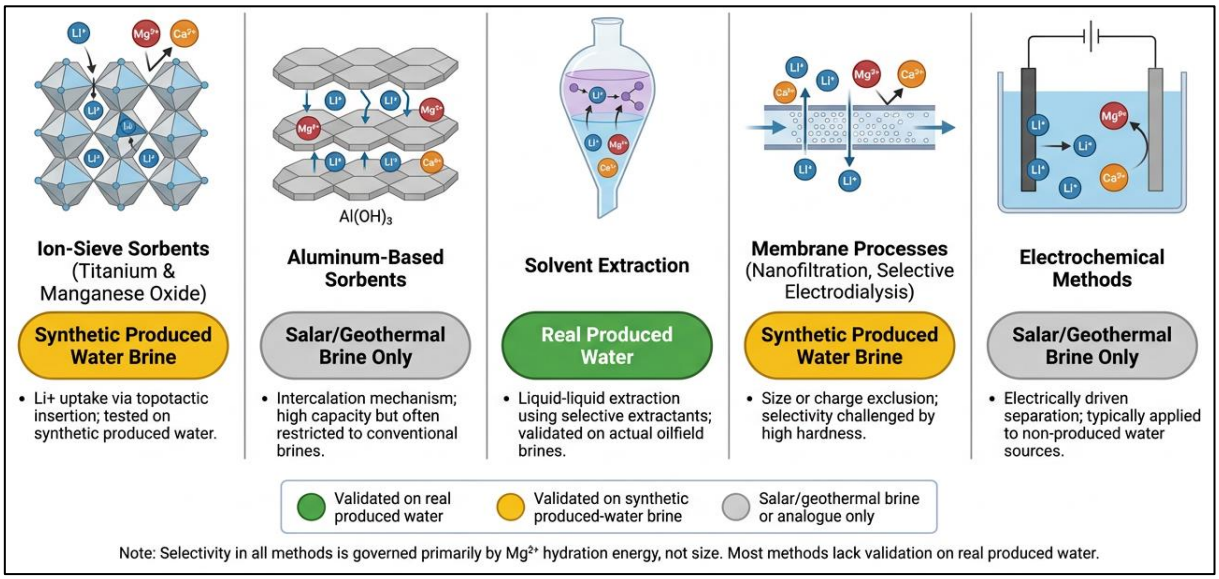


Fig 3 DLE technology families considered in this review and the highest level of evidence identified for each on produced water. Green: tested on real oilfield or gas-field brine. Yellow: tested on synthetic brines designed to represent produced water. Grey: tested on salar, geothermal, or generic synthetic brine only.

➢ *Fundamentals of Ion Selectivity: Ionic Radius, Hydration, and Lattice Energetics*

Selectivity within each DLE family can be attributed to three interrelated properties of the competing cations. The Shannon ionic radius of six-coordinate Li^+ is approximately 0.76 Å, close to that of Mg^{2+} (0.72 Å) but smaller than that of Ca^{2+} (1.00 Å) (Shannon, 1976); therefore, Li^+ and Mg^{2+} cannot be distinguished by bare-ion size alone. Li/Mg selectivity depends on charge density and its consequence, hydration energy. With twice the charge of Li^+ and a similar radius, Mg^{2+} has a substantially more negative hydration free energy: approximately −475 kJ/mol for Li^+, −1,830 kJ/mol for Mg^{2+}, and −1,505 kJ/mol for Ca^{2+} (Marcus, 1991; Fig. 4). Mg^{2+} therefore retains its hydration shell much more strongly and must shed more of it to enter a dehydrating site. This hydration penalty, rather than bare radius, is the primary physical basis for the Li-over-Mg selectivity of the sorbent, solvent-extraction, and membrane systems reviewed below. For Ca^{2+}, its larger bare radius adds a size-exclusion contribution to its already substantial hydration penalty.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

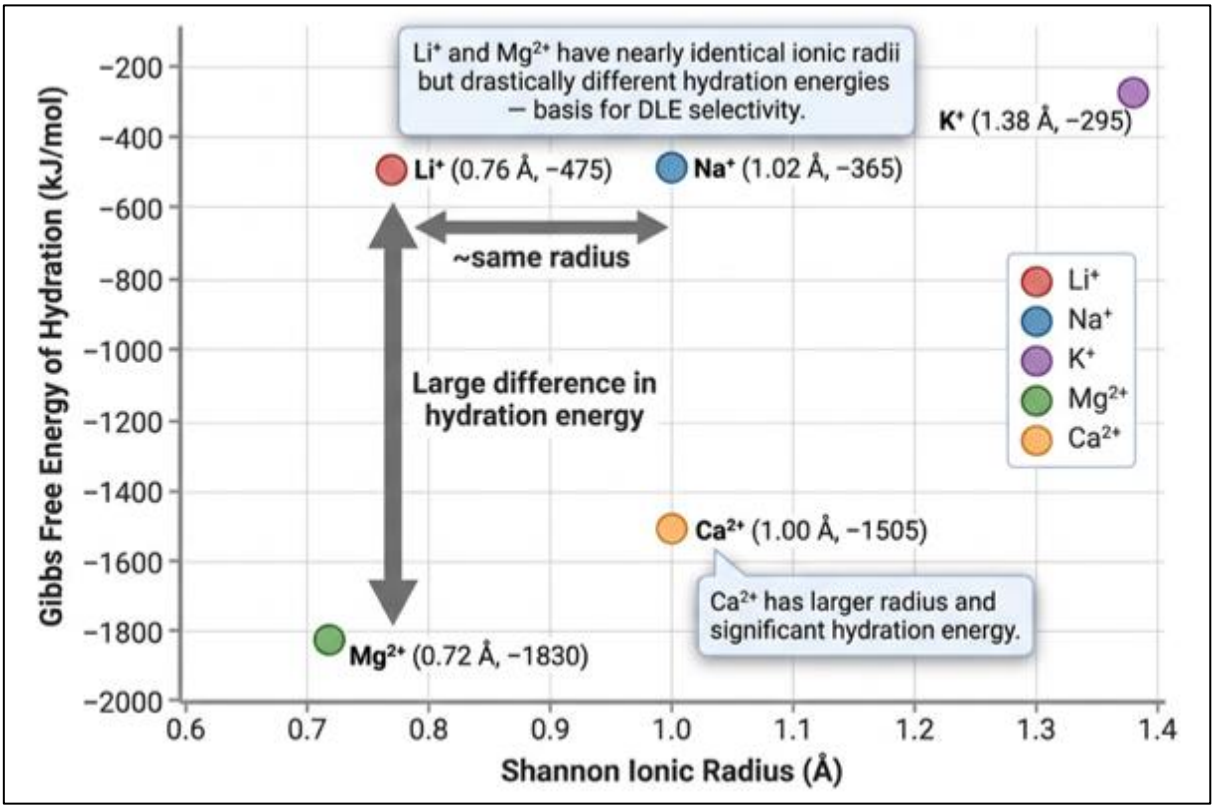


Fig 4 Shannon ionic radius (sixfold coordination) versus Gibbs free energy of hydration for Li^+, Na^+, K^+, Mg^{2+}, and Ca^{2+}. Radii are from Shannon (1976), and hydration free energies are from Marcus (1991). Li^+ and Mg^{2+} have nearly identical radii but markedly different hydration energies.

➢ *Titanium- and manganese-oxide Ion-Sieve Sorbents*

Lithium ion-sieve (LIS) sorbents take up Li^+ via topotactic insertion into a host oxide framework that remains largely intact during sorption and acid elution. Two host chemistries predominate: lithium manganese oxides (LMO), primarily spinel-type $Li_{1.6}Mn_{1.6}O_4$ and related compositions, and lithium titanium oxides (LTO), primarily the H_2TiO_3 form derived from Li_2TiO_3 (Xu et al., 2016). In LMO, uptake occurs at redox-type sites associated with Mn(III) in the precursor spinel and at ion-exchange sites associated with Mn(IV). In both families, interstitial sites accommodate dehydrated Li^+, whereas Mg^{2+} and Ca^{2+} are excluded primarily because removing their hydration shells requires more energy.

Reported LMO capacities generally range from 10–40 mg Li per g of sorbent, depending on the synthesis method and precursor treatment. The primary limitation is manganese dissolution and spinel degradation during repeated acid elution (Xu et al., 2016). A Mn–Ti mixed ion sieve tested in artificial salt-lake brine achieved a maximum adsorption capacity of 32.32 mg/g, with desorption exceeding 90% and a recovery efficiency of 81.42% by the fifth cycle (Ding et al., 2023). In synthetic shale-gas produced water, an H_2TiO_3 sorbent achieved a maximum capacity of 2.58 mmol/g (approximately 17.9 mg/g), with lithium preferentially recovered over other cations when a pH buffer was used (Jang and Chung, 2018).

Equilibrium uptake is usually fitted with a Langmuir isotherm:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \quad (3)$$

And the approach to equilibrium with a pseudo-second-order rate law:

$$\frac{dq}{dt} = k_2 (q_e - q)^2 \quad (4)$$

Where q_e and q represent the equilibrium and time-dependent uptake (mg/g), respectively; q_{max} denotes the monolayer capacity; K_L is the Langmuir constant; C_e is the equilibrium concentration; and k_2 is the rate constant. A good fit to the pseudo-second-order model is often interpreted as evidence of chemisorption. However, this fit alone does not establish the rate-limiting mechanism (Simonin, 2016), and intraparticle diffusion should be evaluated separately.

➢ *Aluminum-Based Sorbents*

Aluminum-based sorbents with the general composition $LiCl{\cdot}2Al(OH)_3{\cdot}nH_2O$ operate through a mechanism distinct from that of oxide ion sieves. Li^+ occupies octahedral vacancies within the $Al(OH)_3$ layers, while chloride and water occupy the interlayer spaces and balance the charge; consequently, lithium is taken up and released together with chloride. Partial delithiation through a dilute aqueous wash creates vacant sites that are refilled upon contact with brine. Because these sorbents do not require acid for elution, they avoid the structural degradation associated with oxide ion

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

sieves. However, they have a lower capacity and produce a dilute eluate; the wash step also consumes fresh water in proportion to the cycle frequency (Vera et al., 2023). Aluminum-based sorption is the only DLE route with a long commercial operating record, having been used at Salar del Hombre Muerto in Argentina since the late 1990s (Vera et al., 2023). Peer-reviewed data on aluminum-based sorbents for produced water remain limited. One laboratory study of shale-gas produced water reported selectivity for lithium over sodium, calcium, and magnesium, as well as stable performance over five adsorption–desorption cycles (Pan et al., 2024).

➢ *Solvent Extraction*

Solvent extraction transfers lithium into an immiscible organic phase containing a neutral organophosphorus extractant, most commonly tributyl phosphate (TBP) or tri(2-ethylhexyl) phosphate (TOP) (Wang et al., 2025), typically with ferric chloride as a co-extractant. Fe(III) forms the $FeCl_4^-$ anion, and lithium is extracted as an ion pair with the solvated cation; therefore, high chloride activity is required (Ochromowicz et al., 2024). Selectivity is again governed by hydration energy, as the extractant must replace the cation's hydration shell. This barrier is substantially lower for Li^+ than for Mg^{2+} or Ca^{2+}. Performance is quantified using the distribution ratio and separation factor.

$$D = \frac{[Li]_{org}}{[Li]_{aq}} \quad (5)$$

$$SF_{Li/Me} = \frac{D_{Li}}{D_{Me}} \quad (6)$$

Where $[Li]_{org}$ and $[Li]_{aq}$ are equilibrium concentrations in the organic and aqueous phases, and *Me* is *Mg* or *Ca*.

A TOP–$FeCl_3$ system applied to actual high-calcium oilfield brine (52.1 g/L Mg^{2+} and 84.4 g/L Ca^{2+}) achieved a single-stage lithium extraction rate of 77%, with Li/Mg and Li/Ca separation factors of 5,737 and 96, respectively. Multi-stage stripping concentrated the eluate to 15.35 g/L Li at a stripping efficiency of 96.5%, while carbonate precipitation produced Li_2CO_3 with a purity exceeding 99.5% (Wu et al., 2025). However, the transition from synthetic to actual brine is not always as successful. A TBP–$FeCl_3$–$AlCl_3$ system that extracted 91% of the lithium from synthetic brine achieved an extraction rate of only approximately 32% from actual, evaporated high-calcium brine obtained from a Permian gas well in Poland. The authors attributed this decline to the salting-in effect of Ca, K, and Mg, which were absent from the synthetic feed (Ochromowicz et al., 2024). Researchers have tested two-stage processes for shale-gas produced water, with an initial stage to remove divalent cations, using synthetic Marcellus-type brines (Jang et al., 2017; Lee and Chung, 2020). Additionally, an ionic-liquid system incorporating adsorption and precipitation pretreatment achieved an overall recovery rate of 71.5% from simulated shale-gas produced water (Lee et al., 2025).

➢ *Membrane Processes*

Membrane-based lithium recovery includes nanofiltration, which rejects multivalent cations through size and charge exclusion while allowing monovalent lithium to pass, and selective electrodialysis with monovalent-selective ion-exchange membranes, which separates Li^+ from divalent cations under an electric field (Li et al., 2019). Bipolar membrane electrodialysis (BMED) serves a different purpose: it converts a purified LiCl stream into LiOH and HCl rather than separating Li/Mg. Membrane cost and fouling are key variables for this process family; for example, membrane cost contributes to the capital and operating costs of the combined nanofiltration and membrane distillation–crystallization route evaluated by Rabbani et al., 2026. We found no peer-reviewed membrane study conducted using real oilfield produced water.

➢ *Electrochemical Methods*

Electrochemical DLE employs lithium-selective intercalation electrodes, typically olivine $LiFePO_4$ or spinel λ-MnO_2, to capture lithium from brine under an applied current and release it into a separate recovery solution. This approach combines the host-lattice selectivity of ion-sieve sorbents with electrochemical control over uptake and release, thereby avoiding acid elution (Battistel et al., 2020). Related methods include electrochemically switched ion exchange and capacitive deionization using selective electrodes. Most reported studies have focused on salar, geothermal, or synthetic brines. Testing with actual oilfield brine remains limited, as organic compounds and high concentrations of divalent ions can passivate electrodes.

➢ *Cross-Technology Synthesis: Validated Findings on Produced Water*

Across the five families, one pattern is evident: most mechanistic and performance data are derived from synthetic or salar brine rather than actual produced water (Table 2). The TOP–$FeCl_3$ study of real oilfield brine indicates that solvent extraction can tolerate very high divalent-ion loads (Wu et al., 2025); however, Ochromowicz et al. (2024) demonstrate that performance on synthetic feeds can overstate field performance by several-fold. Accordingly, claims regarding produced-water treatment should be evaluated considering the evidence supporting them. Future studies should report results for real brine from a named formation alongside any synthetic benchmark.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

Table 2 Comparison of DLE Technology Families Applicable to Oilfield-Produced Water, Including the Highest Level of Evidence Identified for Each.

Technology	Mechanism	Reported performance	Main limitations	Highest evidence level for produced water
LMO ion sieve	Li^+ insertion in spinel; redox and ion-exchange sites	~10–40 mg/g (Xu et al., 2016)	Mn dissolution during acid elution	Salar or synthetic brine
H_2TiO_3 ion sieve	Li^+/H^+ exchange in layered titanate	2.58 mmol/g (~17.9 mg/g) on synthetic shale-gas produced water (Jang and Chung, 2018); capacity lowered by organics (Jang and Chung, 2019)	Lower capacity than LMO; sensitivity to organics	Synthetic produced water
Al-based sorbent	Li^+ in octahedral layer vacancies, Cl^- in interlayer	Commercial on salar brine since the late 1990s (Vera et al., 2023)	Low capacity; dilute eluate; wash-water demand	Salar brine (commercial); shale-gas produced water, laboratory scale (Pan et al., 2024)
Solvent extraction	Solvated Li^+ extracted as ion pair with $FeCl_4^-$	77% single stage, SF(Li/Mg) 5,737, SF(Li/Ca) 96 on real oilfield brine (Wu et al., 2025); ~32% on real gas-field brine versus 91% on synthetic brine (Ochromowicz et al., 2024)	Extractant and Fe losses; high chloride needed; organics	Real oilfield and gas-field brine
Membranes (NF, selective ED)	Size and charge exclusion; field-driven monovalent transport	Li^+/Mg^{2+} separation factors of 2.6–10.4 (up to 1815 for MOF-based NF membranes); Li^+ recovery >95% for SLM and S-ED, >83% for membrane CDI, and >73% for MDC; separation factors of 4–51 for ion-imprinted membranes (IIM) and 99–5312 for ion-sieve membranes (LISM), with adsorption capacities of 4–50 and 10.3–27.8 mg/g, respectively on synthetic solutions(Li et al., 2019)	Fouling, scaling, membrane cost	Salar or synthetic brine only
Electrochemical	Li^+ intercalation into $LiFePO_4$ or λ-MnO_2 electrodes	Reviewed by Battistel et al. (2020)	Electrode passivation; scale-up	Salar, geothermal or synthetic brine

SF = Separation Factor (Eq. 6). Capacities in mg Li per g Sorbent. Energy Demand is Not Tabulated Because Technology-Resolved Data for Produced Water are Not Available (Section 7.4).

V. SYNTHESIS OF TECHNOLOGICAL, ECONOMIC, REGULATORY, AND ENVIRONMENTAL CONSIDERATIONS

➢ *Prices and Production Economics*

Lithium prices have been highly volatile. In 2025, the US lithium carbonate price averaged approximately $9,000 per tonne, 31% lower than in 2024 and substantially below the 2022 peak (USGS, 2026). Treat industry forecasts anticipating a recovery toward higher prices as scenarios rather than projections (Fitzgerald and Spiller, 2025). A comparative techno-economic analysis of solvent extraction, adsorption, and combined nanofiltration/membrane distillation-crystallization assessed capital and operating costs, net present value, rate of return, and payback across eleven lithium carbonate price scenarios ranging from $10,000 to $50,000 per tonne over a 15-year period (Rabbani et al., 2026). This is the most directly comparable multi-technology assessment identified, although it was not conducted using produced water.

Site-specific data from Arkansas illustrate the gap between demonstrated and assumed recovery. Anson Resources has reported a DLE recovery rate of 91% and a lithium carbonate processing recovery rate of 88%, implying a combined recovery rate of approximately 80%. By contrast, another project has not published recovery data; therefore, analysts must assume a 90% recovery rate for modeling purposes (Fitzgerald and Spiller, 2025). The definitive feasibility study for the Southwest Arkansas project, filed in October 2025, reports an all-in Class III capital cost estimate of US$1.45 billion, average cash operating costs of US$4,516/t over the project life, and an average brine grade of 481 mg/L. However, it does not report a recovery percentage (Smackover Lithium, 2025). This information is disclosed by the company and has not been peer-reviewed.

➢ *Royalty and Ownership of Brine*

Regulatory terms are a first-order economic variable that the technical literature rarely considers. In May 2025, the Arkansas Oil and Gas Commission approved the state's first

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

royalty on lithium extracted from brine: 2.5% of the value of lithium carbonate equivalent for the Reynolds Brine Production Unit of the Smackover Lithium joint venture, in addition to the existing per-acre brine fee (Arkansas Oil and Gas Commission, 2025). Royalty rates, unitization rules, and the legal status of lithium in brine vary across states and provinces, and project economics cannot be transferred between jurisdictions without accounting for these factors.

➢ *Environmental Considerations: Water, Waste, and Reinjection*

Produced-water DLE avoids the long residence times and extensive land requirements associated with conventional salar evaporation ponds, an advantage frequently cited in the literature. However, it does not eliminate the existing burdens of produced-water management. Spent brine reinjected for disposal or enhanced oil recovery presents the same induced-seismicity and groundwater-protection considerations as produced water managed without lithium recovery (Ellsworth, 2013). DLE also adds burdens, including freshwater use for sorbent washing and elution; acid and base consumption; spent sorbent and manganese generated by LMO degradation; organic extractant losses; and softening sludge (Vera et al., 2023). We found no life-cycle assessment specific to produced water that quantifies the carbon footprint, water use, and waste generated per tonne of lithium carbonate, compared with salar evaporation and spodumene mining.

➢ *Energy Consumption*

Energy consumption in an integrated DLE operation is driven primarily by brine pumping, which scales with the volume of brine processed per tonne of lithium and thus varies inversely with feed concentration, as well as by downstream conversion. Lithium hydroxide production via electrolysis or BMED is more electricity-intensive than carbonate precipitation. Published energy estimates for integrated DLE operations are drawn mainly from industry and consulting reports; we found no peer-reviewed, technology-resolved energy data for produced-water feedstock.

➢ *Knowledge Gaps and Research Priorities*

Synthesizing Sections 3 to 7, seven research priorities stand out as more important than incremental gains in the peak performance of any single technology.

- Volume-Weighted Resource Assessment. Basin comparisons should integrate lithium concentration with produced-water volume (Eq. 1) and well decline, ensuring that low-concentration, high-volume basins, such as the Permian, are evaluated based on lithium flux rather than concentration alone.
- Temporal and spatial variability. Brine chemistry varies over the lifetime of a well and between flowback and produced water. Repeated sampling of the same wells is necessary to characterize feed variability for process design.
- Basin-specific thermodynamic modeling. Applying the Pitzer framework (Section 4) to the complete major-ion compositions of Smackover, Leduc, Bakken, and Wolfcamp brines would enable quantitative predictions of lithium activity and extraction equilibria.
- Real-Brine Validation. DLE processes should be evaluated using real brine from identified formations spanning the range documented in Section 3. Synthetic benchmarks should also be reported, given the several-fold differences observed between synthetic and real feeds (Section 6.4).
- Complete performance reporting. Report separation factors, capacity or flux, cycle stability, and lithium losses in pretreatment together for the same material and brine, which is rarely done today (Table 2).
- Energy, water, and waste accounting. Technology-specific data on energy use, freshwater consumption, reagent consumption, and waste generation in produced-water DLE are necessary to support a credible life-cycle comparison with salar and hard-rock production.
- Integrated models. A framework that links brine geochemistry, pretreatment requirements, extraction performance, regulatory conditions, and project economics would enable site-specific recovery and cost estimates based on geological characterization data.

VI. CONCLUSIONS

Lithium concentrations in oilfield-produced water represent a basin-specific geological resource. Basin-wide concentrations range from approximately 16 mg/L in the Wolfcamp to more than 170 mg/L in the Smackover. At the well level, concentrations in southern Arkansas range from 1 to 477 mg/L, reflecting evaporite dissolution, silicate–water–rock interaction, and brine mixing. Because concentration alone does not fully indicate resource significance, volume-weighted lithium flux should also be reported.

The selectivity of the primary DLE families rests on a common physical principle. Li^+ and Mg^{2+} have nearly identical ionic radii; therefore, separation depends primarily on the substantially greater hydration free energy of Mg2+. Ion-sieve, aluminum-based, solvent-extraction, membrane, and electrochemical methods exploit this contrast in distinct ways. However, most performance data come from synthetic brines or salar brines. The limited tests conducted with real brine demonstrate both high selectivity (a Li/Mg separation factor of 5,737) and substantial performance losses compared with synthetic feeds (91% versus approximately 32% extraction). Accordingly, validation using real produced water remains a critical step.

Economic viability depends on factors that the technical literature rarely considers together: price volatility, combined recovery across DLE and refining, and regulatory terms, such as the 2.5% lithium royalty approved in Arkansas in 2025. The environmental case for produced-water DLE is plausible but remains unquantified because this feedstock's water use, waste streams, and energy demand have not been assessed. Integrating geological characterization, process validation, and techno-economic and environmental assessments within a single framework is the key step needed to advance produced-water lithium from promise to production.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

➢ *CRediT Authorship Contribution Statement*

Raymond Aderoju, Mojibola Afolabi, Tracy Chukwuma, Olanrewaju Ayodele, Toheeb Hamzat, Ayodeji Aderibigbe, Olasunkanmi Olagboye: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

➢ *Funding*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

➢ *Declaration of Competing Interests*

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

➢ *Data Availability*

No new data were generated. All values are taken from the cited sources. The plotting scripts used to produce Figs. 1 to 4 are available from the author on request.

➢ *Highlights*

- Lithium in produced water is basin-specific, not a property of oilfield brine
- Basin-mean Li ranges from 16 mg/L (Wolfcamp) to over 170 mg/L (Smackover)
- Li/Mg selectivity in DLE arises mainly from Mg^{2+} hydration energy, not size
- Few DLE methods have been tested on real oilfield brine rather than analogs
- Resource assessments should weight Li concentration by produced-water volume

REFERENCES

[1]. Arkansas Oil and Gas Commission, 2025. Approval of the application of SWA Lithium/Smackover Lithium for a lithium royalty, Reynolds Brine Production Unit, 28 May 2025. Arkansas Department of Energy and Environment, Little Rock. Approved 28 May 2025. Department announcement: https://ee.arkansas.gov/news-post/oil-and-gas-commission-approves-swa-lithium-llcs-additional-compensationrate-for-lithium/. Order number: [032-2025-05].

[2]. Battistel, A., Palagonia, M.S., Brogioli, D., La Mantia, F., Trócoli, R., 2020. Electrochemical methods for lithium recovery: a comprehensive and critical review. Advanced Materials 32, 1905440. https://doi.org/10.1002/adma.201905440

[3]. Butler, K.L., Munk, L.A., Boutt, D.F., Morris, N., Kennedy, J., Saha, P., Blake, M.R., Custado, M.J., Ibarra, D.E., 2025. The origin and enrichment of sedimentary basin lithium brines: a case study from the Upper Devonian Leduc Formation, Alberta Basin, Canada. Economic Geology 120(3), 649–662.

[4]. Collins, A.G., 1974. Geochemistry of Liquids, Gases, and Rocks from the Smackover Formation. Report of Investigations 7897, US Bureau of Mines, Washington, DC.

[5]. Ding, Y., Nhung, N.T.H., An, J., Chen, H., Liao, L., He, C., Wang, X., Fujita, T., 2023. Manganese-titanium mixed ion sieves for the selective adsorption of lithium ions from an artificial salt lake brine. Materials 16, 4190. https://doi.org/10.3390/ma16114190

[6]. Dugamin, E.J.M., Richard, A., Cathelineau, M., Boiron, M.-C., Despinois, F., Brisset, A., 2021. Groundwater in sedimentary basins as potential lithium resource: a global prospective study. Scientific Reports 11, 21091. https://doi.org/10.1038/s41598-021-99912-7

[7]. Eccles, D.R., Berhane, H., 2011. Geological introduction to lithium-rich formation water with emphasis on the Fox Creek area of west-central Alberta (NTS 83F and 83K). ERCB/AGS Open File Report 2011-10, Energy Resources Conservation Board, Edmonton.

[8]. Ellsworth, W.L., 2013. Injection-induced earthquakes. Science 341, 1225942. https://doi.org/10.1126/science.1225942

[9]. Ettehadi, A., Chuprin, M., Mokhtari, M., Gang, D., Wortman, P., Heydari, E., 2024. Geological insights into exploration and extraction of lithium from oilfield produced-water in the USA: a review. Energy & Fuels 38, https://doi.org/10.1021/acs.energyfuels.4c00732

[10]. European Union, 2024. Regulation (EU) 2024/1252 of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials (Critical Raw Materials Act). Official Journal of the European Union, L series, 3 May 2024.

[11]. Fitzgerald, F., Spiller, B., 2025. Can emerging industrial technologies compete? Scoping the market viability of direct lithium extraction in the United States. RFF Report 25-16. Resources for the Future, Washington, DC. https://www.rff.org/publications/reports/can-emerging-industrial-technologies-compete-scoping-the-market-viability-of-direct-lithium-extraction-in-the-united-states/

[12]. Gerardo, S., Song, W., 2025. Lithium recovery from U.S. oil and gas produced waters: resource quality and siting considerations. Environmental Science: Water Research & Technology. https://doi.org/10.1039/d4ew00422a

[13]. Harvie, C.E., Møller, N., Weare, J.H., 1984. The prediction of mineral solubilities in natural waters: the Na–K–Mg–Ca–H–Cl–SO4–OH–HCO3–CO3–CO2–H2O system to high ionic strengths at 25 °C. Geochimica et Cosmochimica Acta 48, 723–751. https://doi.org/10.1016/0016-7037(84)90098-X

[14]. Hitchon, B., Underschultz, J.R., Bachu, S., 1993. Industrial Mineral Potential of Alberta Formation Waters. Open File Report 1993-15, Alberta Research Council, Alberta Geological Survey, Edmonton, 92 p.

[15]. Jang, E., Jang, Y., Chung, E., 2017. Lithium recovery from shale gas produced water using solvent

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

extraction. Applied Geochemistry 78, 343–350. https://doi.org/10.1016/j.apgeochem.2017.01.016

[16]. Jang, Y., Chung, E., 2018. Adsorption of lithium from shale gas produced water using titanium-based adsorbent. Industrial & Engineering Chemistry Research 57, 8381–8387. https://doi.org/10.1021/acs.iecr.8b00805

[17]. Jang, Y., Chung, E., 2019. Lithium adsorptive properties of H2TiO3 adsorbent from shale gas produced water containing organic compounds. Chemosphere 221, 75–80. https://doi.org/10.1016/j.chemosphere.2019.01.032

[18]. Kaplan, R., Mamrosh, D., Salih, H.H., Dastgheib, S.A., 2017. Assessment of desalination technologies for treatment of a highly saline brine from a potential CO2 storage site. Desalination 404, 87–101.

[19]. Karuppasamy, K., Mayyas, A., Alsheinat, E., Hassan-Beck, H., Alfantazi, A., 2024. Exploring lithium extraction technologies in oil and gas field-produced waters: from waste to valuable resource. Chemical Engineering Journal Advances 20, 100680. https://doi.org/10.1016/j.ceja.2024.100680

[20]. Knierim, K.J., Blondes, M.S., Masterson, A.L., Freeman, P.A., McDevitt, B., Herzberg, A.H., Li, P., Mills, C., Doolan, C., Jubb, A.M., Ausbrooks, S.M., Chenault, J., 2024a. Evaluation of the lithium resource in the Smackover Formation brines of southern Arkansas using machine learning. Science Advances 10, eadp8149. https://doi.org/10.1126/sciadv.adp8149

[21]. Knierim, K.J., Masterson, A.L., Freeman, P.A., McDevitt, B., Herzberg, A.H., Li, P., Mills, C., Doolan, C., Jubb, A.M., Ausbrooks, S.M., Chenault, J., 2024b. Lithium resource in the Smackover Formation brines of southern Arkansas. U.S. Geological Survey Fact Sheet 2024-3052. https://doi.org/10.3133/fs20243052

[22]. Kumar, A., Fukuda, H., Hatton, T.A., Lienhard, J.H., 2019. Lithium recovery from oil and gas produced water: a need for a growing energy industry. ACS Energy Letters 4, 1471–1474. https://doi.org/10.1021/acsenergylett.9b00779

[23]. Lee, J., Chung, E., 2020. Lithium recovery by solvent extraction from simulated shale gas produced water: impact of organic compounds. Applied Geochemistry 116, 104571. https://doi.org/10.1016/j.apgeochem.2020.104571

[24]. Lee, J., Mangiri, R., Jang, G., Jbari, O., Lee, Y., & Chung, E. (2025). Selective lithium recovery from simulated shale gas produced water using an ionic liquid extraction system. *Desalination*, 119498.

[25]. Li, X., Mo, Y., Qing, W., Shao, S., Tang, C.Y., Li, J., 2019. Membrane-based technologies for lithium recovery from water lithium resources: a review. Journal of Membrane Science 591, 117317. https://doi.org/10.1016/j.memsci.2019.117317

[26]. Mackey, J., Bain, D.J., Lackey, G., Gardiner, J., Gulliver, D., Kutchko, B., 2024. Estimates of lithium mass yields from produced water sourced from the Devonian-aged Marcellus Shale. Scientific Reports 14, 8813. https://doi.org/10.1038/s41598-024-58887-x

[27]. Marcus, Y., 1991. Thermodynamics of solvation of ions. Part 5. Gibbs free energy of hydration at 298.15 K. Journal of the Chemical Society, Faraday Transactions 87, 2995–2999. https://doi.org/10.1039/FT9918702995

[28]. Marza, M., Ferguson, G., Thorson, J., Barton, I., Kim, J.-H., Ma, L., McIntosh, J., 2024. Geological controls on lithium production from basinal brines across North America. Journal of Geochemical Exploration 257, 107383. https://doi.org/10.1016/j.gexplo.2023.107383

[29]. Moldovanyi, E.P., Walter, L.M., 1992. Regional trends in water chemistry, Smackover Formation, southwest Arkansas: geochemical and physical controls. AAPG Bulletin 76, 864–894.

[30]. Munk, L.A., Hynek, S.A., Bradley, D.C., Boutt, D., Labay, K., Jochens, H., 2016. Lithium brines: a global perspective. Reviews in Economic Geology 18, 339–365.

[31]. Nicot, J.-P., Darvari, R., Eichhubl, P., Scanlon, B.R., Elliott, B.A., Bryndzia, L.T., Gale, J.F.W., Fall, A., 2020. Origin of low salinity, high volume produced waters in the Wolfcamp Shale (Permian), Delaware Basin, USA. Applied Geochemistry 122, 104771. https://doi.org/10.1016/j.apgeochem.2020.104771

[32]. Nicot, J.-P., Ko, L.T., Darvari, R., Elliott, B.A., 2026. Dissolved lithium content and aqueous geochemistry of the Haynesville Shale of East Texas and Northwest Louisiana. Applied Geochemistry 198, 106707. https://doi.org/10.1016/j.apgeochem.2026.106707

[33]. Ochromowicz, K., Zabłocka-Malicka, M., Chojnacka, I., Worsa-Kozak, M., 2024. Assessing the viability of integrating evaporation and solvent extraction systems for lithium recovery from low-grade brines. Processes 12, 1453. https://doi.org/10.3390/pr12071453

[34]. Pan, Y., Ji, B., Zhang, W., Xia, Y., Li, Q., Rena, B., 2024. Selective extraction of lithium from shale gas produced water using an aluminum-based adsorbent. Green and Smart Mining Engineering 1(2), 208–219. https://doi.org/10.1016/j.gsme.2024.05.002

[35]. Peterman, Z.E., Thamke, J.N., Futa, K., Oliver, T.A., 2017. Characterization and origin of brines from the Bakken–Three Forks petroleum system in the Williston Basin, USA. The Mountain Geologist 54, 203–222.

[36]. Pitzer, K.S., 1973. Thermodynamics of electrolytes. I. Theoretical basis and general equations. Journal of Physical Chemistry 77, 268–277. https://doi.org/10.1021/j100621a026

[37]. Pitzer, K.S., Kim, J.J., 1974. Thermodynamics of electrolytes. IV. Activity and osmotic coefficients for mixed electrolytes. Journal of the American Chemical Society 96, 5701–5707. https://doi.org/10.1021/ja00825a004

[38]. Rabbani, M., Muthoni, F., Rabbani, M.T., Nili, S., Sharifian, S., Vahidi, E., 2026. Comparative techno-economic analysis of direct sustainable lithium extraction from brine: solvent extraction, adsorption, and combined nanofiltration/membrane distillation-crystallization. ACS Sustainable Resource Management 3, 1570–1580.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26oct1285

[39]. Samuel, O., Othman, M. H. D., Kamaludin, R., Sinsamphanh, O., Abdullah, H., Puteh, M. H., ... & Mamah, S. C. (2022). Oilfield-produced water treatment using conventional and membrane-based technologies for beneficial reuse: A critical review. Journal of Environmental Management, 308, 114556. Scanlon, B.R., Reedy, R.C., Male, F., Walsh, M., 2017. Water issues related to transitioning from conventional to unconventional oil production in the Permian Basin. Environmental Science & Technology 51, 10903–10912. https://doi.org/10.1021/acs.est.7b02185

[40]. Shannon, R.D., 1976. Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. Acta Crystallographica A32, 751–767. https://doi.org/10.1107/S0567739476001551

[41]. Simonin, J.-P., 2016. On the comparison of pseudo-first order and pseudo-second order rate laws in the modeling of adsorption kinetics. Chemical Engineering Journal 300, 254–263. https://doi.org/10.1016/j.cej.2016.04.079

[42]. Smackover Lithium, 2025. Smackover Lithium files definitive feasibility study for its South West Arkansas project. News release, 14 October 2025, Lewisville, AR. https://www.standardlithium.com/_resources/news/nr-20251014b.pdf

[43]. Stringfellow, W.T., Dobson, P.F., 2021. Technology for the recovery of lithium from geothermal brines. Energies 14, 6805. https://doi.org/10.3390/en14206805

[44]. Stueber, A.M., Pushkar, P., Hetherington, E.A., 1984. A strontium isotopic study of Smackover brines and associated solids, southern Arkansas. Geochimica et Cosmochimica Acta 48, 1637–1649.

[45]. USGS (U.S. Geological Survey), 2026. Lithium. In: Mineral Commodity Summaries 2026. U.S. Geological Survey, Reston, VA. https://pubs.usgs.gov/periodicals/mcs2026/mcs2026-lithium.pdf

[46]. Vera, M.L., Torres, W.R., Galli, C.I., Chagnes, A., Flexer, V., 2023. Environmental impact of direct lithium extraction from brines. Nature Reviews Earth & Environment 4, 149–165. https://doi.org/10.1038/s43017-022-00387-5

[47]. Wang, L., Zhang, J., Meng, S., Wu, H., Zhao, Y., Meng, Z., Feng, L., Wang, H., Cheng, Y., Yang, L., Liu, H., 2025. Recovery of lithium from high Mg2+/Li+ ratio brine using a novel solvent extraction system TOP-FeCl3-MIBK. Desalination 599, 118445. https://doi.org/10.1016/j.desal.2024.118445

[48]. Wu, H., Zhang, J., Dong, T., Cheng, Y., Hu, X., Liu, H., & Yang, L. (2025). Direct and highly efficient lithium extraction from real oilfield brine via a selective TOP-FeCl3 system. Separation and Purification Technology, 363, 132086. Xu, X., Chen, Y., Wan, P., Gasem, K., Wang, K., He, T., Adidharma, H., Fan, M., 2016. Extraction of lithium with functionalized lithium ion-sieves. Progress in Materials Science 84, 276–313. https://doi.org/10.1016/j.pmatsci.2016.09.004