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Advances, Mechanisms, and Hybrid Strategies in Low-Salinity and Smart Water Enhanced Oil Recovery: A Comprehensive Review

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Abstract

Low-salinity waterflooding (LSW) and smart water injection have emerged as leading techniques in Enhanced Oil Recovery (EOR), with significant potential to optimize oil production from sandstone and carbonate reservoirs. Over the past decade, advancements in the understanding of ion exchange, wettability modification, multi-ion interactions, and hybridization with chemical EOR methods have shifted LSW from a laboratory observation to a field-validated recovery strategy. This review integrates current progress in low-salinity, smart water, and hybrid LSW-chemical methods, highlighting breakthrough findings on nanoparticle synergy, polymer interactions, wettability alteration, pH effects, salinity thresholds, and reservoir mineralogical compatibility. Detailed evaluations of experimental, numerical, and pilot-scale field studies are presented, offering a structured perspective on the mechanisms and practical conditions that govern LSW success. Emerging hybrid methods combining surfactants, alkali, nanoparticles, and polymers with LSW demonstrate measurable improvements in sweep efficiency, mobility control, interfacial tension (IFT) reduction, and tertiary recovery potential. Overall, this review provides an extensive synthesis of current trends, implementation challenges, and research opportunities for future EOR operations.

Keywords : Low-salinity waterflooding, Smart water flooding, Wettability alteration, Hybrid EOR, Nanoparticle-assisted EOR, Carbonate and sandstone reservoirs

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1. Introduction

Low-salinity waterflooding has evolved into a major EOR technique after numerous studies confirmed its ability to enhance oil production beyond conventional seawater or formation water. Foundational research has demonstrated that salinity reduction triggers multiple reservoir-scale interactions including wettability alteration, multi-ion exchange, detachment of crude oil components, clay surface activation, pH elevation, and fines mobilization (Austad et al., 2011). A series of experimental works further refined mechanistic understanding, showing that LSW efficiency depends strongly on crude oil composition, reservoir mineralogy, connate water chemistry, and injection-water ion composition (Kakati et al., 2020; Mohammadkhani et al., 2018). Other researchers explored its performance across carbonate and sandstone systems, demonstrating variable but often substantial improvements in secondary and tertiary recovery stages (Ben Mahmud et al., 2019; Darvish Sarvestani et al., 2019).
Recent reviews have expanded the scope to hybrid methods, integrating nanoparticles, chemical surfactants, alkalis, and polymers with low-salinity water to exploit IFT reduction, wettability

modification, and mobility control simultaneously (Pourafshary & Moradpour, 2019; Mumbere et al., 2025). Furthermore, numerical modeling and field-scale evaluations, including pilot studies, have demonstrated real-world application feasibility and highlighted operational constraints (Brantson et al., 2020; Srivastava et al., 2024). More recently, smart water concepts — in which ionic composition is intentionally engineered — have gained prominence, supported by patent and article reviews showing rapid technological innovation (Quintella et al., 2025).
Given the diversity of mechanisms, conditions, and hybrid strategies, a detailed and structured review is necessary. This paper consolidates experimental findings, theoretical insights, hybrid EOR advances, and field experiences to provide a comprehensive understanding of LSW and smart water EOR systems.

2. Mechanisms of Low-Salinity Waterflooding

Low-salinity waterflooding operates through a combination of physicochemical interactions that collectively enhance oil displacement efficiency. Key among these mechanisms is **wettability alteration**, where the reservoir surface shifts from oil-wet toward more water-wet states, thereby improving spontaneous imbibition and reducing residual oil saturation. Studies have shown that reducing salinity disrupts the equilibrium of ion-exchange reactions at the rock–fluid interface, promoting desorption of polar organic components and enabling greater water accessibility to pore surfaces (Austad et al., 2011).

Another mechanism is **multi-ion exchange (MIE)**, particularly prominent in carbonate reservoirs where ions like SO_4^{2-}, Mg^{2+}, and Ca^{2+} interact with rock minerals. This interaction leads to the release of adhered organic acidic compounds, ultimately improving oil mobility (Darvish Sarvestani et al., 2019). A reduction in salinity also encourages **expansion of the electrical double layer**, which weakens the adhesive forces between clays and crude oil molecules, facilitating oil release.

Additionally, **pH elevation** during LSW can occur due to mineral dissolution and ion exchange, which leads to in-situ formation of soap-like compounds that reduce interfacial tension. Fines migration, though sometimes a risk, can create beneficial pore-channel redirection and improve sweep efficiency when controlled appropriately. Experimental studies in sandstone systems have shown improved oil displacement when clays act as active sites for these ionic interactions (Kakati et al., 2020).

Other reported mechanisms include decreased crude oil viscosity under certain ionic conditions and enhanced mobility ratios due to reduced water salinity. In carbonate reservoirs, the presence of anhydrite, dolomite, or calcite strongly influences which mechanisms dominate. Collectively, these interactions illustrate that LSW is not governed by a singular mechanism but rather a synergistic system dependent on mineralogy, salinity gradient, and crude oil chemistry.

3. Low-Salinity Waterflooding in Sandstone Reservoirs

In sandstone reservoirs, LSW has been widely documented as an effective EOR technique due to its interaction with clay minerals. Numerous studies have shown that sandstone rocks containing kaolinite, illite, and smectite respond strongly to salinity reduction, making the mechanism of double-layer expansion particularly relevant. For instance, experiments indicate that reducing injection-water salinity from seawater levels to diluted brines results in significant desorption of polar organic molecules adhered to clay surfaces, thereby releasing trapped oil droplets (Ben Mahmud et al., 2019).

A key factor in sandstone LSW is the role of **connate water**, which has been shown to influence the ionic gradients necessary for wettability alteration. Mohammadkhani et al. (2018) demonstrated that reservoirs with high initial connate salinity experience stronger LSW responses because the salinity contrast drives ion diffusion and exchange processes. Secondary LSW often performs exceptionally well in sandstones due to the active surfaces of clay minerals.

A critical insight from laboratory studies is that oil composition—particularly the presence of acidic and polar components—plays a defining role in determining efficiency. Light oils with low acid numbers typically exhibit smaller LSW benefits, although certain studies show improvements under optimized conditions (Kakati et al., 2020). The influence of divalent ions such as Ca^{2+} and Mg^{2+} is also significant: their removal or controlled reintroduction greatly affects clay stability and wettability behavior.

In heavy oil sandstones, the LSW response becomes more complex due to viscosity effects. Bhicajee and Romero-Zerón (2021) showed that low-salinity schemes combined with alkali are more effective for heavy oils, as alkali mitigates high oil viscosity by producing in-situ surfactants. Overall, LSW in sandstone reservoirs remains one of the most consistent and experimentally validated EOR methods when mineralogy and water chemistry are properly assessed.

Table 1. Comparison of Key Mechanisms and Responses in Low-Salinity EOR

Parameter	Sandstone Reservoirs	Carbonate Reservoirs	Hybrid LSW–Chemical Systems
Dominant Mechanisms	Double-layer expansion, Clay interaction, Surface charge alteration	Multi-ion exchange (SO_4^{2-}, Mg^{2+}, Ca^{2+}), Surface charge reversal	Combined wettability alteration + IFT reduction + mobility control
Wettability State Before LSW	Usually water-wet to mixed-wet	Mostly oil-wet	Mixed-wet or engineered wet-state
Effective Salinity Range	500–5,000 ppm	2,000–10,000 ppm depending on ion compositions	Tuned based on surfactant/alkali/polymer compatibility
Role of Connate Water	High influence; salinity contrast drives ion exchange	Moderate; carbonate surfaces require specific ions	Critical for polymer/alkali stability
Oil Type Response	Effective for medium/light oil; enhanced with alkali for heavy oil	Effective for medium oil; improved by sulfate-modified brine	Broad applicability across oil viscosities
Key Limitations	Fines migration risk; clay instability	Requires engineered brine; limited clay content	Cost, chemical adsorption, potential incompatibilities
Incremental Recovery Trends	5–12% OOIP	3–10% OOIP	10–25% OOIP depending on system
Best Performing Additives	Alkali for heavy oil, controlled divalent ions	Sulfate-enriched brines, engineered Mg^{2+}/Ca^{2+}	Surfactants, polymers, nanoparticles

Parameter	Sandstone Reservoirs	Carbonate Reservoirs	Hybrid LSW–Chemical Systems
Temperature Dependency	Moderate	High; better performance at higher temp	Depends on chemical formulation
Field Applicability	Widely demonstrated	Growing; requires ion-engineered brine	Emerging but promising for complex reservoirs

4. Low-Salinity and Smart Waterflooding in Carbonate Reservoirs

Carbonate reservoirs present a more complex environment for LSW due to their predominantly oil-wet nature and limited clay content. However, breakthrough studies highlighted the crucial role of certain ions—particularly sulfate, magnesium, and calcium—in enabling wettability alteration even in these mineralogically distinct systems (Austad et al., 2011). Smart water flooding, which involves engineering the ionic signature of injected brine, has become increasingly important in carbonates to enhance LSW efficiency.

Experiments by Darvish Sarvestani et al. (2019) confirmed that tuning the ratios of SO_4^{2-}, Mg^{2+}, and Ca^{2+} significantly improves tertiary oil recovery in carbonates. These ions interact with carbonate rock surfaces to facilitate detachment of acidic oil components. Smart water formulations often involve enriching brines with sulfate, which acts as a catalyst for surface reactions that promote water-wet conditions.

Furthermore, the temperature of carbonate reservoirs plays a vital role, as elevated temperatures accelerate ion exchange processes. Certain reservoirs with high temperatures show stronger LSW responses because magnesium and calcium adsorption equilibria shift more favorably at higher thermal conditions.

Field observations in carbonates also validate laboratory findings. Pilot studies in offshore carbonate fields show incremental recovery when smart-water modified brines replace conventional seawater injection (Srivastava et al., 2024). In some cases, LSW effects alone are moderate, but when combined with surfactants or nanoparticles, carbonate reservoirs exhibit substantial improvements in both capillary desaturation and microscopic displacement efficiency.

Overall, smart water in carbonates has transitioned from a theoretical concept to a practical engineering approach, supported by both mechanistic insight and field data.

5. Hybrid Low-Salinity–Chemical EOR Methods

Hybrid EOR strategies integrating low-salinity water with chemical agents—such as polymers, alkalis, surfactants, and nanoparticles—have gained considerable momentum. These methods leverage the strengths of LSW mechanisms while addressing its limitations related to mobility control, IFT reduction, and sweep uniformity. One major advantage of hybrid systems is the synergy between LSW-induced wettability alteration and surfactant-driven IFT reduction, which together produce greater oil mobilization than either method alone (Pourafshary & Moradpour, 2019).

Nanoparticles have emerged as a transformative additive in LSW due to their ability to adsorb at oil–water interfaces, reduce IFT, and adjust wettability. The recent review by Mumbere et al. (2025) shows substantial incremental oil recovery when nanoparticles are dispersed in low-salinity brines, with significant enhancements observed in both light and heavy oil systems. These nanoparticles also prevent surfactant degradation and stabilize emulsions beneficial for improved displacement.

Polymer-LSW hybrids have been particularly successful in reservoirs requiring viscosity control to mitigate fingering effects. Brantson et al. (2020) developed a specialized hybrid low-salinity polymer flooding simulator that demonstrated improved sweep efficiency and more stable mobility ratios. Alkali-LSW hybrids also provide notable benefits, particularly in viscous oil reservoirs where alkaline reactions generate natural surfactants and reduce crude oil viscosity.

Collectively, hybrid systems represent the cutting-edge stage of LSW development, enabling tailored EOR strategies that maximize displacement efficiency and reservoir contact.

6. Numerical Modeling, Simulation, and Field Applications

Numerical modeling has played a crucial role in validating LSW mechanisms and predicting field performance. Models incorporating ion exchange behavior, wettability alteration kinetics, and double-layer interactions allow reservoir engineers to simulate complex physicochemical processes occurring during injection. Brantson et al. (2020) developed a hybrid modeling framework that couples chemical EOR processes with salinity-dependent rock–fluid interactions, providing more realistic predictions for hybrid LSW-CEOR flooding.

Field-scale applications further solidify the viability of LSW. A notable example is the pilot study conducted in a Western Offshore Basin, where Srivastava et al. (2024) reported early positive observations from low-salinity injection, supported by both laboratory and simulation results. The pilot showed promising indicators such as reduction in water cut, delayed breakthrough, and moderate yet significant incremental oil recovery.

Smart water techniques have also progressed into real field operations. Patents and global case studies compiled by Quintella et al. (2025) show significant industry interest and a rapid increase in engineered brine technologies. These include sulfate-enriched seawater, low-calcium brines, and mixed-ion brine formulations tailored to specific reservoir conditions.

While numerous field trials confirm LSW feasibility, challenges remain—such as scaling issues, reservoir heterogeneity, and uncertainty in ion-rock reaction timescales. Nevertheless, simulation-based optimization continues to improve prediction accuracy, making LSW increasingly reliable for full-field deployment.

Conclusion

Low-salinity and smart waterflooding have transitioned from laboratory concepts to field-validated EOR strategies, supported by strong mechanistic understanding and promising field results. The technology's adaptability across sandstone and carbonate reservoirs, combined with rapid advancements in smart water formulation, makes LSW one of the most dynamic areas in modern petroleum engineering. Hybridization with chemical and nanomaterial-based EOR techniques further amplifies recovery potential, addressing limitations related to sweep efficiency, mobility, and IFT reduction. Numerical and pilot-study evidence underscores its practical viability, while ongoing innovation continues to refine and expand its application. Overall, LSW stands as a robust, cost-effective, and environmentally favorable technique poised to play a significant role in future oil recovery operations.

Reference:

- Gbadamosi, A., Patil, S., Al Shehri, D., Kamal, M. S., Hussain, S. M. S., Al-Shalabi, E. W., & Hassan, A. M. (2022). Recent advances on the application of low salinity waterflooding and chemical enhanced oil recovery. Energy Reports, 8, 9969–9996. https://doi.org/10.1016/j.egyr.2022.08.001
- Quintella, C. M., Rodrigues, P. D., Nicoleti, J. L., & Hanna, S. A. (2025). Comprehensive Review of Smart Water Enhanced Oil Recovery Based on Patents and Articles. Technologies, 13(10), 457. https://doi.org/10.3390/technologies13100457
- Kakati, A., Kumar, G., & Sangwai, J. S. (2020). Oil Recovery Efficiency and Mechanism of Low Salinity-Enhanced Oil Recovery for Light Crude Oil with a Low Acid Number. ACS Omega, 5(3), 1506–1518. https://doi.org/10.1021/acsomega.9b03229
- Ben Mahmud, H., Arumugam, S., & Mahmud, W. (2019). Potential of Low-Salinity Waterflooding Technology to Improve Oil Recovery. In Enhanced Oil Recovery Processes - New Technologies. IntechOpen. https://doi.org/10.5772/intechopen.88082
- Pourafshary, P., & Moradpour, N. (2019). Hybrid EOR Methods Utilizing Low-Salinity Water. In Enhanced Oil Recovery Processes - New Technologies. IntechOpen. https://doi.org/10.5772/intechopen.88056
- Mumbere, W., Sagala, F., Gupta, U., & Bbosa, D. (2025). Reservoir Potential Unlocked: Synergies Between Low-Salinity Water Flooding, Nanoparticles and Surfactants in Enhanced Oil Recovery─A Review. ACS Omega, 10(29), 31216–31261. https://doi.org/10.1021/acsomega.5c02533
- Darvish Sarvestani, A., Ayatollahi, S. & Bahari Moghaddam, M. Smart water flooding performance in carbonate reservoirs: an experimental approach for tertiary oil recovery. J Petrol Explor Prod Technol 9, 2643–2657 (2019). https://doi.org/10.1007/s13202-019-0650-9
- Mohammadkhani, S., Shahverdi, H., & Esfahany, M. N. (2018). Impact of salinity and connate water on low salinity water injection in secondary and tertiary stages for enhanced oil recovery in carbonate oil reservoirs. Journal of Geophysics and Engineering, 15(4), 1242–1254. https://doi.org/10.1088/1742-2140/aaae84
- Bhicajee, P., & Romero-Zerón, L. (2021). Effect of different low salinity flooding schemes and the addition of alkali on the performance of low-salinity waterflooding during the recovery of heavy oil from unconsolidated sandstone. Fuel, 289, 119981. https://doi.org/10.1016/j.fuel.2020.119981
- Srivastava, V. R., Sarma, H. K., & Gupta, S. K. (2024). Low-Salinity Waterflooding for EOR in Field A of Western Offshore Basin: A Pilot Study Analysis with Laboratory and Simulation Studies—Early Observations. Energies, 17(9), 2149. https://doi.org/10.3390/en17092149
- Austad, T., Shariatpanahi, S. F., Strand, S., Black, C. J. J., & Webb, K. J. (2011). Conditions for a Low-Salinity Enhanced Oil Recovery (EOR) Effect in Carbonate Oil Reservoirs. Energy & Fuels, 26(1), 569–575. https://doi.org/10.1021/ef201435g
- Brantson, E. T., Ju, B., Opoku Appau, P., Akwensi, P. H., Peprah, G. A., Liu, N., Aphu, E. S., Annan Boah, E., & Aidoo Borsah, A. (2020). Development of hybrid low salinity water polymer flooding numerical reservoir simulator and smart proxy model for chemical enhanced oil recovery (CEOR). Journal of Petroleum Science and Engineering, 187, 106751. https://doi.org/10.1016/j.petrol.2019.106751