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Sustainable EOR Through Ion-Engineered Produced Water: A Smart Water Feasibility Study

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ABSTRACT
As the international oil and gas sector focuses on sustainable, cost-effective enhanced oil recovery (EOR) methods globally and in regions that face water scarcity, smart water flooding has surfaced as an effective solution. The tuning of injection water's ionic composition improves oil displacement efficiency by altering reservoir wettability. However, using freshwater or seawater still presents environmental and economic challenges. This research explores reusing produced water as a sustainable base fluid for smart-water EOR techniques. Produced water was treated through low-cost ion-tuning methods, i.e. dilution and selective ion exchange, to match standard smart-water formulations through its ionic composition for both sandstone and carbonate reservoirs. More than 85% of treated samples met the desired ionic balance, while the modified ion composition increased SO_4^{2-} from 1,010 mg/L to 2,500 mg/L suggests an approximate 10% improvement in oil recovery based on correlations previously developed to explain wettability alteration. This work presents a low-cost solution to produced-water recycling which has the capacity to scale up and would suit Bangladesh's ongoing and consistent development towards sustainable water management and EOR.

Keywords: Smart Water, Ion Tuning Produced Water, Enhanced Oil Recovery, Dilution-Enrichment Strategy, Wettability Alteration

1. Introduction

The worldwide shift toward environmentally friendly power systems has created strong demands for the oil and gas industry to extract more from current reserves while controlling ecological impacts. The solution to this problem depends on Enhanced Oil Recovery (EOR) which uses chemical and water-based methods to extract between 30% and 60% or more of reservoir oil [1] The first two extraction methods produce between 20% and 40% of the total reserve [2] [3]. Among the newer innovations, smart water flooding has emerged as a low-cost, environmentally friendly alternative to chemical flooding, gaining rapid attention in sandstone and carbonate reservoirs like [4].

Smart water is essentially engineered water, formulated by tuning the ionic composition primarily ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Na^{+} to promote favorable rock–fluid interactions such as wettability alteration, multi-ion exchange, and electrostatic double layer expansion [5]. The processes work to decrease capillary forces, which enable released oil to move freely, thus improving the overall recovery efficiency. Different laboratory and field tests have confirmed the effectiveness of ion-modified water injections to boost the recovery of oil by 5-15% in sandstone and carbonate formations. [6]. A recent experimental study (2024) on the sequence injection effect of seawater and smart water in offshore carbonate reservoirs reported quantitative gains, with oil recovery increasing by up to 43 % OOIP when smart water was injected first and 7.9 % additional oil when injected after seawater, confirming the strong influence of injection sequencing and ionic composition on recovery efficiency[7].

Innovation, intelligent water design is typically dependent on expensive laboratory operations, ion-specific testing, and most commonly, the presence of base water (e.g., seawater or simulated brines) not available or impractical in inland, desert, or underdeveloped regions. In addition, in countries such as Bangladesh, where oil and gas exploration is largely based on onshore gas fields (e.g., Titas, Habiganj, Kailashtila), the lack of seawater, small chemical supply logistics, and fragmented laboratory facilities are a hindrance to the implementation of classical EOR technologies In the meantime, the natural gas and petroleum industries has another age-old in the shape of produced water management and disposal that, in most instances, surpasses the hydrocarbon production quantity. Globally, over 250 million barrels of produced water are generated daily [8]. The water contains salt which makes it saline along with various dissolved ions and hydrocarbons and occasionally heavy metals. The disposal process for this water involves either reinjection or evaporation which produces no beneficial results while creating potential environmental dangers. [9].

The research introduces a novel approach for determining the suitability of ion-modified produced water as a base fluid in smart water applications for enhanced oil recovery. The method depends on free ionic composition information from major oil-producing areas, which include the Permian Basin, to analyze Na^{+}, Ca^{2+}, Cl^{-}, Mg^{2+} , and SO_4^{2-} ions that form the basis of smart water design [10] [11]. The study uses dilution models and ion substitution analysis, and ionic index

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comparisons to predict the theoretical changes in waste-produced water when transformed into smart water suitable for EOR. The method operates as a practical solution for areas that lack laboratory facilities.

The regional data indicate that Bangladesh's onshore gas fields at Sylhet and Habiganj produce water containing elevated salt levels and high sodium chloride concentrations, together with trace amounts of iron, manganese, and nickel [12]. The disposal of these hydrochemical characteristics creates environmental difficulties, yet they show promise for ion-tuning applications. The inland position of Bangladesh, combined with its absence of ocean water resources, makes it possible to create a cost-effective and sustainable EOR method by using controlled dilution and ionic modification of saline effluents. The reuse framework would fit into Petrobangla's current gas system to support the Vision 2041 goals for sustainable production and resource management.

The study investigates high salinity produced water to function as smart water for enhanced oil recovery (EOR) through affordable ionic tuning methods. The Permian Basin serves as the source for real produced water data, which enables a data-driven framework to match benchmark smart water formulations through ionic deviation analysis and dilution modeling, and stoichiometric enrichment for sandstone and carbonate reservoirs. The approach also assesses suitability for Bangladesh's inland fields, where lab and seawater access are limited, and it offers a scalable, low-carbon EOR approach aligned with SDGs 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

2. Methodology

2.1. Data Acquisition: Produced Water Chemistry

The Permian Basin produced water from Jal, New Mexico, in the USA, served as the study's representative dataset. The data for ionic composition resulted from public sources, which included assessments of regional brine disposal facilities and large-scale hydrochemical basin studies. Jal Basin data is a comparable analogue for Bangladesh's inland onshore gas fields because they exhibit similar salinity, Na^+–Cl^- and Ca^{2+}/Mg^{2+} ion dominance, making them suitable candidates for a preliminary ion tuning feasibility analysis. All calculations are based on an isothermal system, at 25°C (room temperature) and standard atmospheric pressure (1 atm), and ideal solution behavior. These assumptions provide realistic reservoir conditions in the dilution, enrichment, and deviation analysis and provide a comparative baseline when examining or testing Bangladesh reservoirs.

Table 1. Chemical characteristics of the Permian Basin (Jal, New Mexico, USA) produced water [13]

Ion	Concentration (mg/L)
Na^+	42,470 ± 2,093
Ca^{2+}	4,247 ± 752
Mg^{2+}	727 ± 54
K^+	805 ± 230
Cl^-	65,800 ± 1,600
SO_4^{2-}	1,010 ± 9

2.2 Smart Water Target Composition

Smart water EOR relies on matching target ions to trigger mechanisms like wettability alteration and ion exchange. It is successful due to the strategic alteration of the injection brine's ionic composition, which induces favorable physicochemical interactions between reservoir rock, oil, and water. Discovery of these target ions is the first step towards developing an efficient injection plan.

Table 2. Recommended Ionic Targets and Their Roles in Smart Water EOR Design

Ion	Recommended Target	Role in EOR
SO_4^{2-} (Sulfate)	2,000–4,000 mg/L	Effective in wettability alteration, 5–18% OOIP gain in cores [14]
Ca^{2+} (Calcium)	1,500–2,000 mg/L	Supports multivalent ion exchange, enhances oil detachment, especially with SO_4^{2-}[14]
Mg^{2+} (Magnesium)	~1,000 mg/L	Enhances wettability alteration under high-temperature conditions (>90 °C).[15]
Na^+ / Cl^-	10,000–15,000 mg/L	Moderate salinity promotes ionic interaction, reduces scaling, and improves sweep. [16][17]

2.3 Deviation Calculation

To determine the level of ionic tuning needed for transforming produced water (PW) into smart water (SW), the study uses a specific quantitative deviation metric. The evaluation method determines the amount of each ion in produced water by comparing it to the target concentrations which form the smart water formulation. The calculation of ion i deviation follows this procedure:

$$Deviation(\%) = \left|\frac{CPW,i - CSW,i}{CSW,i}\right| \times 100 \quad (1)$$

The first equation provides two variables, which represent the produced water ion concentration (mg/L) as CPW,i, and the target ion concentration for smart water (mg/L) as CSW,i. The normalized percentage difference measure functions as a comparison tool for scientists because it allows them to evaluate ions without needing to understand their initial concentration values. The water chemistry analysis identifies ions that require concentration adjustments through dilution or enrichment, or substitution because their measured values exceed the established smart water standards.

2.4 Ion Tuning Strategy

Ion tuning describes the process scientists use to adjust water chemistry through controlled methods, which create specific ionic compositions needed for smart water flooding operations (low salinity waterflooding or LSWF). The process of low salinity waterflooding (LSWF) changes the wettability of reservoir rock and modifies the interfacial tension (IFT) between oil and water, which results in better oil recovery [18]The procedure follows two main steps to achieve this goal. The first method requires using deionized water or formation-compatible low-salinity water to dilute the main monovalent ions (Na^+ and Cl^-) until the total salinity reaches acceptable limits. The required volume of freshwater for dilution was calculated using a modified form of the standard mass balance equation, $C_1V_1=C_2V_2$ [19], rearranged to express freshwater volume as

$$V_{fw}=V_{pw} \times \left(\frac{Cpw}{Csw} - 1\right) \tag{2}$$

where C_{pw} and C_{sw} are the ion concentrations in produced and target smart water, respectively, and V_{pw} is the initial volume of produced water. Secondly, selective enrichment of deficient potential-determining ions (PDIs), including SO_4^{2-}, Ca^{2+}, and Mg^{2+}. The process of enrichment needs industrial-grade water-soluble salts in the form of sodium sulfate (Na_2SO_4) and calcium chloride ($CaCl_2$) and magnesium sulfate ($MgSO_4$) which are added according to stoichiometric calculations for desired concentration levels The formula for this process is

$$m_{salt}=\frac{\Delta Cion \times Vtotal}{n \times MWion} \times MWsalt \tag{3}$$

Where ΔCion is the increase in ion concentration needed (mg/L), Vtotal is the total volume of water being treated (L), MWsalt is the molar mass of the salt being used for enrichment (g/mol), MWion is the molar mass of the ion being targeted (g/mol), and n is the number of moles of targeted ion contributed per mole of salt used.

3. Reservoir Suitability for Smart Water Flooding

Smart water flooding operation is highly dependent on the mineralogical composition and wettability of the reservoir rock. Smart water solutions interact differently with sandstone and carbonate reservoirs, due to their varied surface charges and ion exchange properties. The carbonate reservoir surfaces usually maintain an oil-wet state with positive charging, but sulfate ions (SO_4^{2-}) bring about wettability changes in these environments. Together with divalent cations such as Ca^{2+} and Mg^{2+}, these ions enhance multicomponent ion exchange (MIE) that promotes water-wet behavior and oil mobility [20]. On the other hand, sandstone formations, especially those containing clay minerals such as Illite and kaolinite, are suitable for low salinity waterflooding (LSWF) processes. Reducing injection water salinity causes double-layer swelling and osmotic pressure change, leading to oil desorption from clay surfaces [15] [21]. However, the high divalent concentration under those conditions can lead to clay swelling or formation damage, which must be stringently controlled by proper brine design. The pre-selection of formation for optimal EOR response will include mineralogy analysis, core wettability characterization, determination of ion exchange capacity, clay content and type, reservoir temperature, and salinity profile.

To evaluate the feasibility of converting produced water (PW) to smart water (SW), ion concentration deviations are calculated.As shown in Figure 1, the Permian Basin PW sample is dominated by monovalent ions (Na^+, Cl^-) and Ca^{2+}, while key divalent ions such as $Mg^{2+}$and SO_4^{2-} are lower than the smart water levels. Na+ is here 327% above target, and Cl- is 339% while SO42- and Mg2+ have 60-93% deficits.

Table 3: Formation Types and Their Smart Water Response Characteristics

Formation Type	Preferred Ion Composition	Sensitivity
Carbonate	High SO_4^{2-}, Ca^{2+}, Mg^{2+}	Responds well to wettability alteration (initially oil-wet, positive surface)
Sandstone	Low salinity, moderate divalent ions	Possibility of clay swelling and needs cautious sal inity control

4. Results and Discussion

4.1 Ionic Deviation Analysis

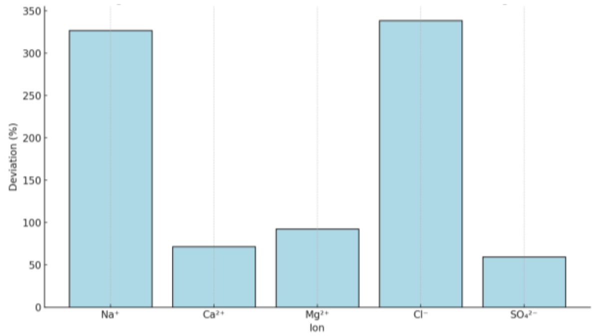

Fig.1: Ion concentration deviation from smart water targets

These findings emphasize the need for both dilution (to reduce monovalent ions) and enrichment (to increase potential-determining ions) to meet their smart water EOR specifications. However, it is not only the disparity in concentration that is relevant; these ionic imbalances exert direct consequences on oil–rock interactions. An excess of Na^+ and Cl^- provides a compressed double layer, keeping surfaces oil wet. Elevating concentrations of divalent cation and potential-determining ion (e.g., SO_4^{2-} and Mg^{2+}) extends the double layer and decreases electrostatic attraction between the oil and rock surface, resulting in oil release.

4.2 Ionic Adjustment through Dilution and Enrichment

Figure 2 shows that the production of smart waters from produced water is fundamentally a two-pronged process that involves (1) dilution of excess ions and (2) intentional selective enrichment of deficient ions. In produced water, the high concentrations of cations Na^+ (42,720 mg/L), Cl^- (65,800 mg/L), and Ca^{2+} (4,247 mg/L) can then be diluted to achieve our target ions for smart water (e.g., $Ca^{2+} \approx$ 1,500 mg/L). This dilution raises the water ionic strength to an optimal level and affects double-layer expansion, promoting oil desorption and recovery. Additionally, deficient ions (particularly ions except Na^+) can be selectively enhanced, such as SO_4^{2-} (~2,000–4,000 mg/L) and Mg^{2+} (~1,000 mg/L), stoichiometrically enhanced with salts such as Na_2SO_4 or $MgSO_4$, enabling multicomponent ion exchange at the rock-brine interface.

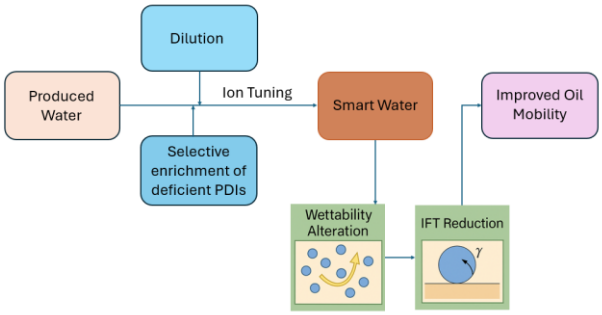

Fig.2: Workflow for Smart Water Generation from Produced Water via Ion Tuning

This multi-component exchange promotes wettability shifts from oil-wet to water-wet systems while decreasing rock-oil-water interfacial tension. Above all, SO_4^{2-} is also a surface-active ion that preferentially attracts divalent ions (Ca^{2+}, and Mg^{2+}) from mineral surfaces, useful to the success of the process. As the SO_4^{2-} interacts with the precipitated divalent ions at the rock surface, the bonding forces that participate in the adhesion and entrapment of oil droplets decrease and facilitate the mobilization of the trapped oil. Ion excursions, therefore, act as mechanisms of EOR rather than simply compositional alterations.

4.3 Produced Water Conditioning for Smart Water Application

Table 4: Ion Overconcentration in Produced Water and Dilution Requirements for Smart Water Optimization

Ion	PW (mg/L)	SW Target (mg/L)	Deviation (%)	Dilution Ratio (V_{fw}/V_{pw})
Na^+	42,720	10,000	327.2%	3.27
Ca^{2+}	4,247	1,500	183.1%	1.83
Cl^-	65,800	10,000	558.0%	5.58

Quantitative deviation analysis revealed that key monovalent and divalent ions in produced water exceeded or fell short of the optimal smart water thresholds. As shown in Table 4, ions such as Na^+, Cl^- , and Ca^{2+} were present at concentrations significantly above their respective smart water targets by 327.2%, 558.0%, and 183.1%. To reduce these to the desired ranges, calculated dilution ratios of 3.27, 5.58, and 1.83 were required, respectively. This would equate to, for every 1,000 L of produced water, a requirement of approximately 3,270 L of freshwater to dilute Na^+ to its smart water range. Surprisingly, Cl^- required the greatest dilution ratio (5.58:1), followed by Na^+ (3.27:1), and then Ca^{2+} (1.83:1). In the field, the choice of freshwater for dilution is extremely critical, both from an availability and a geochemical compatibility perspective. Fresh water may be procured fro m Surface water like rivers, lakes, if salinity is low enough, or treated produced water from local plants through simple desalination (e.g., reverse osmosis). It can also be obtained from Brackish groundwater aquifers with acceptable salinity, which are present in most oil field locations. It should also be verified that the chosen water source does not add scaling ions (e.g., HCO_3^-) or change the desired ionic balance. Compatible formation water also limits clay swelling or fines migration, which is beneficial in low salinity waterflooding.

Table 5. Smart Water Enrichment Strategy: Ion Deficits and Salt Dosage Requirements

Ion	PW (mg/L)	SW Target (mg/L)	Deficit (mg/L)	Enrichment Source Salt	Required Addition (mg/L salt)
Mg^{2+}	727	1,000	273	$MgSO_4$	1,121
SO_4^{2-}	1,010	2,500	1,490	Na_2SO_4	2,212

In contrast, Table 5 outlines the enrichment requirements for underrepresented potential determining ions, Magnesium (Mg^{2+}), at a level of 727 mg/L, needed supplementation with 1,121 mg/L of $MgSO_4 \cdot 7H_2O$ to reach the target of 1,000 mg/L similarly sulfate (SO_4^{2-}), originally at 1,010 mg/L, needed supplementation by 2,212 mg/L of Na_2SO_4 to reach the target of 2,500 mg/L. These adjustments situate the ionic constitution of treated brine to published recipes of smart water demonstrated to enhance wettability alteration as well as the effectiveness of EOR. Collectively, the dilution and enrichment approach form an achievable, quantifiable template for the conversion of high salinity produced water to EOR-capable smart water.

Table 6. Before vs. after ionic profile comparison

Ion	PW (mg/L)	Tuned PW (mg/L)
Na^+	42,720	10,000
Ca^{2+}	4,247	1,500
Mg^{2+}	727	1,000
Cl^-	65,800	10,000
SO_4^{2-}	1,010	2,500
Total Cations	47,694	12,500
Total Anions	66,810	12,500

Table 6 presents a comparison of the original, tuned, and target smart waters' ionic compositions. The dilutions and enrichments reduced total excess Na^+ and Cl^-, optimized the original concentrations of Ca^{2+} and Mg^{2+}, and increased SO_4^{2-} from 1,010 mg/L to 2,500 mg/L, which is within the 2,000–4,000 mg/L range in the literature that indicated oil recovery increased between 5–15% OOIP [13]. This phenomenon is consistent with earlier experimental and model-based studies encouraging the improvement of recoveries to sulfate-driven wettability alteration and ion exchange, thus confirming the current tuning method. After the adjustment, total ions were equilibrated, satisfying compatibility with the reservoir while reducing risks of scaling and clay swelling.

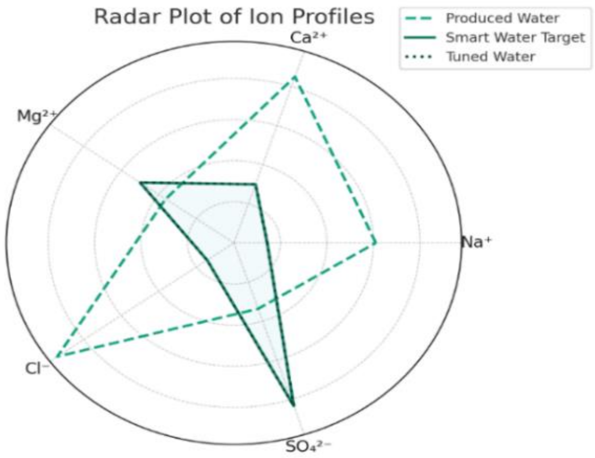

Fig.3: Radar Plot of ion profiles

The radar chart in Figure 3 visually compares the ionic profiles of the original produced water, the target smart water, and the tuned water. It shows that produced water at the beginning, was too rich in Na^{+}, Ca^{2+} and Cl^{-} in quantities not suitable for smart water goals. After diluting the produced water and enriching the sample, the new geometry closely aligns with the geometries of the smart water target signals, which appears to demonstrate that the method is successful at aligning concentration ratios among the ions. This supports that the ion tuning strategy enhances produced water to enhanced oil recovery (EOR) conditions.

4.4 Future Aspects: Application in Bangladesh

As there is increased exploration and production activity in the gas fields of Bangladesh, especially in the eastern regions, the application of ion-engineered produced water provides an excellent chance for low-cost enhanced oil recovery (EOR). Although detailed ionic composition data for produced water are not yet abundant, high salinity and the occurrence of trace metals in available data suggest that in-field tuning of produced water is viable with minimal infrastructure. Its implementation would require only basic chemical dosing and dilution facilities and thus would be suitable for resource-constrained national operators. Next steps will include field sampled water, laboratory assessment of potentially determining ions and small-scale injection trials in depleted or marginal fields to confirm recovery of uplift potential. This process supports Bangladesh's energy transition by allowing for the repurposing of water for sustainable use, reducing the carbon footprint, and transporting hydrocarbon resources more economically.

5. Conclusion

This study proposes a practical methodology for retrofitting high salinity produced water to smart water through ionic composition adjustment by controlled dilution and enrichment. Utilizing real field ionic measurement, principal ions such as Na^{+}, Cl^{-}, Ca^{2+}, Mg^{2+}, and SO_4^{2-} were referenced against best-possible target smart water values to quantify deviation and determine tuning corrections needed. The result indicates that produced water can be systematically engineered to meet smart water needs for use in enhanced oil recovery (EOR) operations, and this is a promising way for water reuse in petroleum operations.

The method is not only technically feasible but also scalable and sustainable. It minimizes the use of fresh water and petrochemicals and encourages the re-use of any available waste streams. While theoretically demonstrated using global basin data, the method also applies to data-poor regions like Bangladesh. Field sampling and simple analysis can be beneficial to utilize these gigantic EOR resources. And finally, this study complements lower-cost and lower-carbon approaches to recovery and long-term visions to utilize freshwater sustainably, promote energy security, and be more intentional in our resource use as a petroleum nation.

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