THERMAL ALTERATION AND WATER DISPLACEMENT EFFICIENCY OF HEAVY OILS: LABORATORY SIMULATION AND EVALUATION OF FIELD SAMPLES

ALTERAREA TERMICĂ ȘI EFICIENȚA DEPLASĂRII APEI ÎN ȚIȚEIURI GRELE: SIMULARE DE LABORATOR ȘI EVALUAREA PROBELOR DE TEREN

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Abstract: *This study investigates the impact of thermal aging on heavy oil properties and displacement efficiency through laboratory simulations of steam-cycled samples from Romania's Suplacu field. Using quartz sand-packed displacement tubes, we analyzed oil-water displacement dynamics under controlled thermal conditions (150°C) and varying steam cycle histories (1–19 cycles). Results demonstrate that increased steam exposure enhances permeability (up to 8,000 mD) and reduces pressure drops (65–160 psi), indicating improved flow efficiency. Thermal alteration also decreased residual carbon content (7.71–9.19%) while increasing total acid number (TAN) (2.38–4.41 mg KOH/g), suggesting simultaneous oil upgrading and oxidative degradation. The experiments reveal that prolonged aging (7 months) and multiple steam cycles significantly improve displacement efficiency, though diminishing returns occur beyond optimal cycle counts. These findings highlight the critical balance between thermal recovery benefits and chemical degradation in heavy oil reservoirs. The study provides actionable insights for optimizing cyclic steam stimulation (CSS) in mature fields, emphasizing the need for customized thermal EOR strategies that account for viscosity reduction, carbon residue evolution, and acidity management.*

.**Keywords**: Thermal EOR, heavy oil, steam cycling, displacement efficiency, residual carbon, acid number, Suplacu field.

Rezumat: *Acest studiu investighează impactul îmbătrânirii termice asupra proprietăților țițeiului greu și a eficienței de deplasare prin simulări de laborator ale probelor tratate cu abur din zăcământul Suplacu din România.*

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Folosind tuburi de deplasare umplute cu nisip de cuarț, am analizat dinamica de deplasare petrol-apă în condiții termice controlate (150°C) și cu istorice variate ale ciclului de abur (1-19 cicluri). Rezultatele demonstrează că expunerea crescută la abur sporește permeabilitatea (până la 8.000 mD) și reduce căderile de presiune (65-160 psi), indicând o eficiență îmbunătățită a curgerii. Alterarea termică a redus, de asemenea, conținutul rezidual de carbon (7,71-9,19%), crescând în același timp numărul total de aciditate (TAN) (2,38-4,41 mg KOH/g), sugerând o îmbunătățire simultană a nivelului de țiței și degradare oxidativă. Experimentele arată că îmbătrânirea prelungită (7 luni) și ciclurile multiple de abur îmbunătățesc semnificativ eficiența de deplasare, deși randamentele descrescătoare apar dincolo de numărul optim de cicluri. Aceste descoperiri evidențiază echilibrul critic dintre beneficiile recuperării termice și degradarea chimică în zăcămintele de țiței greu. Studiul oferă informații practice pentru optimizarea stimulării ciclice cu abur (CSS) în câmpuri mature, subliniind necesitatea unor strategii EOR termice personalizate care să țină cont de reducerea vâscozității, evoluția reziduurilor de carbon și gestionarea acidității.

Cuvinte cheie: EOR termic, țiței greu, cicluri de abur, eficiență de deplasare, carbon rezidual, indice de aciditate, zăcământ Suplacu.

1. Introduction

Heavy oil production, particularly in mature or depleted reservoirs, often faces significant challenges due to high viscosity, low mobility, and reduced displacement efficiency. Thermal enhanced oil recovery (EOR) techniques, such as steam injection and cyclic steam stimulation (CSS), have become increasingly essential for improving recovery factors in heavy oil fields. These methods rely on the principle of viscosity reduction and improved mobility ratio through thermal stimulation. However, the complexity of oil-reservoir interactions under thermal alteration requires laboratory-scale simulation to guide field application [1,2].

Suplacu de Barcău, a mature field in Romania, has been the subject of multiple thermal EOR campaigns. Its heavy crude oils exhibit varying physical properties depending on their production history and number of steam cycles. Understanding how crude oil composition evolves under thermal stress is vital to optimizing displacement processes and enhancing oil recovery [3].

Recent industry reports emphasize the need for customized EOR strategies tailored to specific reservoir characteristics and oil chemistry [4]. New research indicates that steam cycling not only reduces oil viscosity but may also promote thermal cracking, leading to lighter fractions and improved flow [5]. The dynamic relationship between oil saturation, capillary pressure, and thermal alteration further complicates displacement predictions, which necessitates controlled experimental models.

This study aims to reproduce reservoir conditions in a controlled lab environment using displacement tubes filled with quartz sand and different Suplac heavy oils. By simulating thermal alteration at 150°C and subsequent displacement using distilled water, we assess how oil aging and thermal cycles affect permeability, displacement efficiency, and post-displacement oil properties. Key objectives include evaluating changes in permeability, residual oil saturation, carbon residue, and acid number across samples subjected to different steam histories.

2. Literature review

Thermal EOR, especially steam-based techniques, has been widely researched for its role in viscosity reduction and oil mobilization. Nasr and Ayodele [6] provided a comprehensive overview of steam-based recovery, underscoring its effectiveness in heavy oil reservoirs. Sheng [7] and Kumar et al. [8] elaborated on the kinetics of viscosity changes and the critical importance of soak time and temperature in oil flow dynamics.

Laboratory simulation techniques such as sand-packed models have proven essential in evaluating displacement efficiency [9]. These methods mimic porous media behavior and help quantify recovery under controlled conditions. Lashkarbolooki et al. [10] and Zhang et al. [11] demonstrated that thermal cracking during steam treatment modifies the molecular structure of heavy oil, resulting in shifts in total acid number (TAN) and reduction in carbon residue.

Recent studies by Jadhawar et al. [12] and Al-Yousef [13] have linked the number of steam cycles directly to enhanced displacement, noting critical points where additional cycles no longer yield proportionate gains. Masoudi and Torabi [14] investigated the degradation of asphaltenes and its role in altering permeability and residual saturation. Such insights justify integrated lab-field evaluation as implemented in this paper, using representative crude samples with known steam histories from the Suplacu de Barcău field.

Zhang et al. [15] highlighted the changes in acid content of heavy oils after thermal upgrading, suggesting operational adjustments based on chemical evolution. Guo et al. [16] showed that under high-temperature conditions, heavy oils experience structural breakdown, leading to increased light fractions and reactivity. Together, these findings reinforce the value of combining physical lab modeling with thermal EOR chemistry assessments.

3. Methodology

The Suplacu de Barcău field, located in northwestern Romania, is a mature heavy oil reservoir characterized by high-viscosity crude oils exceeding 1000 cP at 40°C. The field has a long history of thermal EOR implementation, including steam flooding and cyclic steam stimulation. Oil samples used in this study were sourced from different wells subjected to varying numbers of steam cycles—ranging from one to nineteen—which significantly influence oil characteristics. Samples from wells such as Sda 2704 (low cycle), Sda 15H (medium cycle), and Sda 4227 (high cycle) were chosen to represent diverse thermal histories. The heterogeneity in steam exposure allows for a comparative analysis of thermal effects on oil behavior during displacement tests. This makes Suplacu de Barcău an ideal field for studying thermal EOR impacts on reservoir fluids.

Some glass tubes (43 cm long, 4.03–4.04 cm diameter) were filled with quartz sand of specified granulometric composition. Each tube was initially saturated with synthetic brine at ambient temperature, followed by injection of heavy crude oil at 40°C under a backpressure of 150 psi and a flow rate of 0.5 ml/min. The saturation periods varied between 2 weeks and 6 weeks, and the tubes were aged for approximately 7 months to simulate reservoir conditions before thermal treatment.

Thermal alteration was simulated by heating the oil-saturated cores to 150°C. After this process, distilled water was injected at room temperature to displace the altered oil and simulate the production phase. Displaced oil samples were collected and subjected to laboratory analysis to determine residual carbon using ASTM D4530 and total acid number (TAN) using ASTM D664. Additionally, porous volume, oil permeability, and pressure drop were measured. Crude oil samples were obtained from Suplacu de Barcău wells (Sda 2704, Sda 15H, Sda 4227), each with known steam cycling histories.

4. General field data description

One of the most durable and prosperous instances of in-situ combustion (ISC) enhanced oil recovery (EOR) in the world is the Suplacu de Barcau oil field, which is situated in Northwestern Romania in the Eastern Pannonian Basin. The field has changed from modest production under solution gas drive to a strong and mature ISC-driven operation that contributes around 10% of Romania's daily oil output since its discovery in the 1956–1960 periods and subsequent production beginning in 1960. With an estimated 310 million barrels of initial original oil in place (OOIP) and 130 million barrels of 2P reserves, the field has a recovery ratio of more than 55% and produces 8,500 barrels per day at the moment [17].

Unconsolidated quartzite sands and other sedimentary intercalations define the shallow, Pliocene-aged clastic deposit known as the Suplacu de Barcau reservoir. The reservoir is highly suited for thermal EOR techniques due to its high porosity (~32%), large oil saturation (79–85%), and high oil viscosity (1,800–2,500 cP). Comprehensive pilot testing of both ISC and steam drive from 1963 to 1970 verified the field's compatibility with ISC, leading to its full commercial deployment beginning in 1971, after early recovery forecasts under natural depletion estimated a meager 9% recovery over 80 years [17].

The geometry of the field at Suplacu required a special ISC procedure. Engineers created a linear combustion front propagation method that is down-structure. Air injection wells placed along East-West lines, 50 to 75 meters apart, served as the foundation for ISC operations starting in 1975. These operations featured complementing cyclic steam stimulation (CSS). About 20% of the increased oil recovery was attributable to this hybrid approach. Production peaked between 1985 and 1991, when air injection rates were at their maximum. An ISC system of 68 daily air injectors and 19–23 CSS wells was supported by 480 of the 2,900 wells that had been dug by 2015 [17].

It has been crucial to oversee and administer the ISC and CSS procedures. Using electric or gas-based techniques, the combustion zone has to be heated to more than 400°C for ISC ignition to be successful. In order to guarantee ideal combustion and identify issues like air channeling or low-temperature oxidation, engineers kept an eye on critical performance metrics including temperature, pressure, gas composition, and hydrogen-to-carbon (H/C) ratios. CSS wells were assessed concurrently for post-injection productivity, temperature and pressure variations, and injection rates. Maintaining ideal air-oil ratios, controlling fluid processing, and handling environmental pollutants like H2S and CO2 were only a few of the many technological difficulties that the sector encountered during its growth. Innovations in combustion modeling, monitoring technology, and well design were used to address these issues. The Suplacu operation's reliance on equipment manufactured mostly in Romania and its strong combustion laboratory partnership with IFP, which supports research into coke formation, wet combustion, and catalytic processes, have been noteworthy strengths [17].

Decades of scientific research have provided important new information on the mineralogical and geochemical changes brought forth by ISC in the reservoir. Changes including the decomposition of clay minerals, the deposition of coke, the creation of organometallic compounds, and the emergence of new minerals like calcium silicates and tobermorite were revealed by investigations. In addition to affecting reservoir characteristics like porosity and permeability, these changes also function as markers of temperature distribution and combustion efficiency. The intricate relationships between fluid and rock systems during ISC have been emphasized by research on the function of clays as catalysts and facilitators of coke deposition [17].

To sum up, the Suplacu oil field is a unique example of an ISC technology's sustained commercial success. It is a global paradigm for heavy oil recovery operations because to its consistent high recovery factor, creative technical solutions, and significant scientific contributions. In order to effectively utilize the remaining reserves, future prospects include the combination of water-flooding, horizontal drilling, and optimized air-steam injection.

5. Results and discussions

The laboratory experiments revealed substantial differences in oil displacement behavior and fluid properties based on steam cycle history. Tube 5 (Sda 2704) exhibited the lowest permeability (3200 mD) and highest pressure drop (160 psi), indicating greater resistance to flow. In contrast, Tube 7 (Sda 4227) had the highest permeability (8000 mD) and the lowest pressure drop (65 psi), suggesting enhanced oil mobility and easier displacement due to multiple steam treatments.

Residual carbon content ranged from 7.71% to 9.19%, with a general trend of decreasing carbon residue with increased steam cycles, reflecting partial thermal upgrading. TAN values increased with the number of steam cycles, peaking at 4.41 mg KOH/g for a sample with 16 steam cycles (Sda 1162). This trend indicates oxidative or thermal degradation processes that elevate the acidity of the crude oil. These observations confirm that steam exposure enhances displacement efficiency while altering chemical properties, which must be considered in field operations.

The following results, which are shown in the following figures and tables, present dynamic displacement experiments using crude oil from the Suplacu oil field. The study focused on understanding oil-water displacement and how thermal treatments alter crude oil properties, particularly coke (carbon residue) formation and acidity levels.

Tube Preparation and Test Setup: Three displacement tubes (Tube 5, 6, and 7) were filled with different Suplacu crude oil types and packed with quartz sand of three distinct grain size distributions: 0.1–0.315 mm (30%), 0.1–0.2 mm (30%), and 0.05–0.1 mm (40%) (see document section on *Pregătirea tuburilor*). Key physical parameters of each tube, including length, diameter, and oil viscosity, are shown in Table 1**.**

Table 1. **Tube and Crude Oil Characteristics**

Displacement Tube	Length (cm)	Diameter (cm)	Tube Volume (ml)	Well	Viscosity (cp at 40°C)
Tube 5 (no temp sensors)	43	4.04	550	Sda 2704	1290
Tube 6 (no temp sensors)	43	4.03	545	Sda 15 H	1934
Tube 7 (no temp sensors)	43	4.04	545	Sda 4227	1290

Displacement Test Conditions: The tubes were initially saturated with water under room temperature at 500 psi. Crude oil was then injected at 40°C and 150 psi at a rate of 0.5 ml/min. Each tube had a porous volume between 218 and 239 ml, and permeability values ranged from 3,200 to 8,000 mD, with Tube 7 having the highest permeability (see Table 2).

Table 2. **Physical Model Characteristics**

Tube	Water Saturation Period	Pause Between Injections	Water Displacement by Oil	Pore Volume (ml)	Oil Permeability (mD)	Pressure Drop (psi)	Aging Period
Tube 5	29.09 – 06.10	6 weeks	16 – 18.11	226	3,200	160	7 months
Tube 6	7 – 12.10	2 weeks	30.10 – 04.11	218	4,100	190	7 months
Tube 7	12 – 19.10	3 days	23 – 26.10	239	8,000	65	7 months

Test 1 – Tube 5 Simulation: A 1:1 blend of oils from wells Sda 15H and Sda 4227 (which had undergone 4 and 6 steam cycles, respectively) was injected at 0.15 ml/min (Test 1, see Figure 1). The oil was thermally altered at 150°C for 24 hours (Figure 2) and then displaced with distilled water for collection and analysis.

Thermal Alteration Effects (Coke and Acidity): The residual carbon content and Total Acid Number (TAN) for various samples with different steam cycling histories are presented in Table 3. Results show:

- Residual carbon (coke) ranged from 7.71% to 9.19%, with a general decrease at higher steam cycle counts.
- TAN values ranged from 2.38 to 4.41 mg KOH/g, increasing in some cases after more steam cycles.

Table 3. **Coke Content and Acidity Analysis**

Well	Sample Code	Steam Cycles	Residual Carbon (%)	TAN (mg KOH/g)
Sda 651	15IOR13300	1	8.11	3.12
Sda 2704	15IOR13700	1	8.34	2.57
Sda 4270	15IOR13800	2	8.79	2.38
Sda 2704	16IOR4406	2	8.15	Not determined
Sda 651	16IOR4407	2	8.02	Not determined
Sda 13H	15IOR13900	3	9.16	2.64
Sda 15H	15IOR14000	3	9.19	2.44
Sda 4270	16IOR04405	3	8.18	Not determined
Sda 15H	16IOR04408	4	9.14	Not determined
Sda 4227	15IOR13500	6	7.71	4.33
Sda 36H	15IOR14100	9	7.97	3.65
Sda 1162	15IOR13600	16	7.95	4.41
Sda 1332	15IOR13400	19	8.26	2.69

This suggests thermal aging reduces coke content but may increase oil acidity, depending on steam exposure and crude composition.

Aging and Recovery Efficiency: The samples aged for seven months showed good oil permeability and displacement, with higher oil recovery noted in more permeable tubes (Tube 7). The progression of displacement and oil-water interaction is illustrated in **Figure 3**.

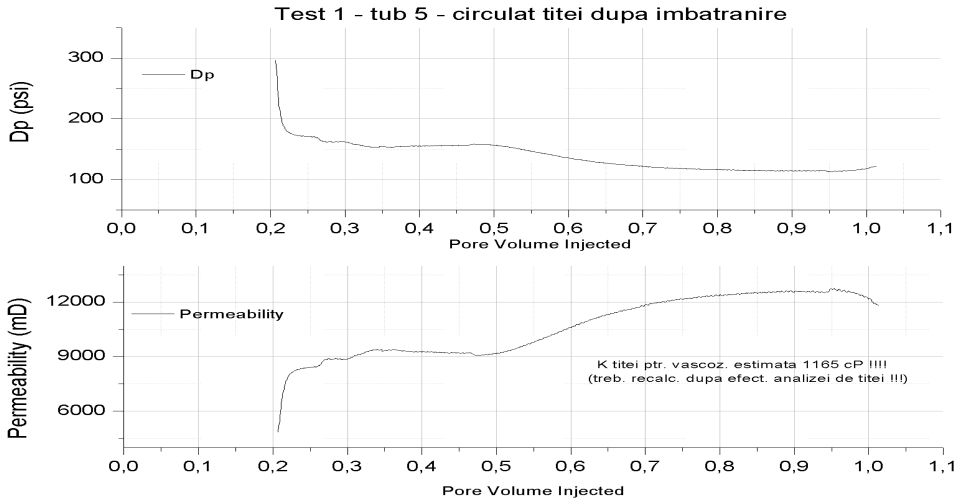

Fig. 1. Thermal Test Setup

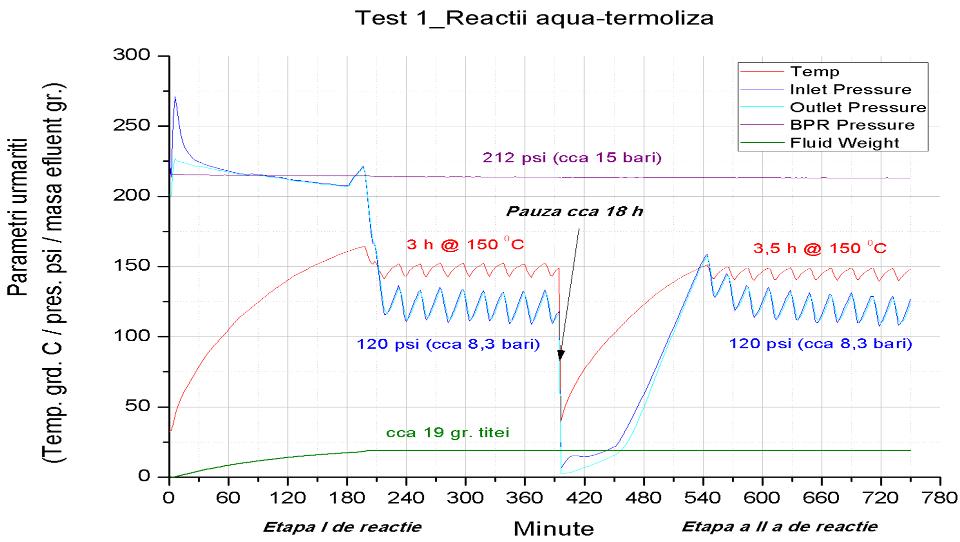

Fig. 2. Oil Alteration Simulation at 150°C

The laboratory experiments demonstrated that thermal aging significantly alters the physical and chemical properties of heavy oils, directly impacting displacement efficiency. Samples subjected to higher numbers of steam cycles (e.g., Sda 4227 with 6 cycles) exhibited higher permeability (8,000 mD) and lower pressure drops (65 psi), indicating improved fluid mobility due to viscosity reduction. In contrast, oils with fewer steam cycles (e.g., Sda 2704 with 1 cycle) showed lower permeability (3,200 mD) and higher flow resistance (160 psi drop), reinforcing the role of thermal exposure in enhancing oil recovery. Additionally, residual carbon content decreased with more steam cycles (from 9.19% to 7.71%), suggesting that thermal cracking breaks down heavy fractions into lighter, more mobile components. However, total acid number (TAN) increased with steam exposure (peaking at 4.41 mg KOH/g), likely due to oxidative degradation, which may necessitate corrosion-resistant materials in field operations.

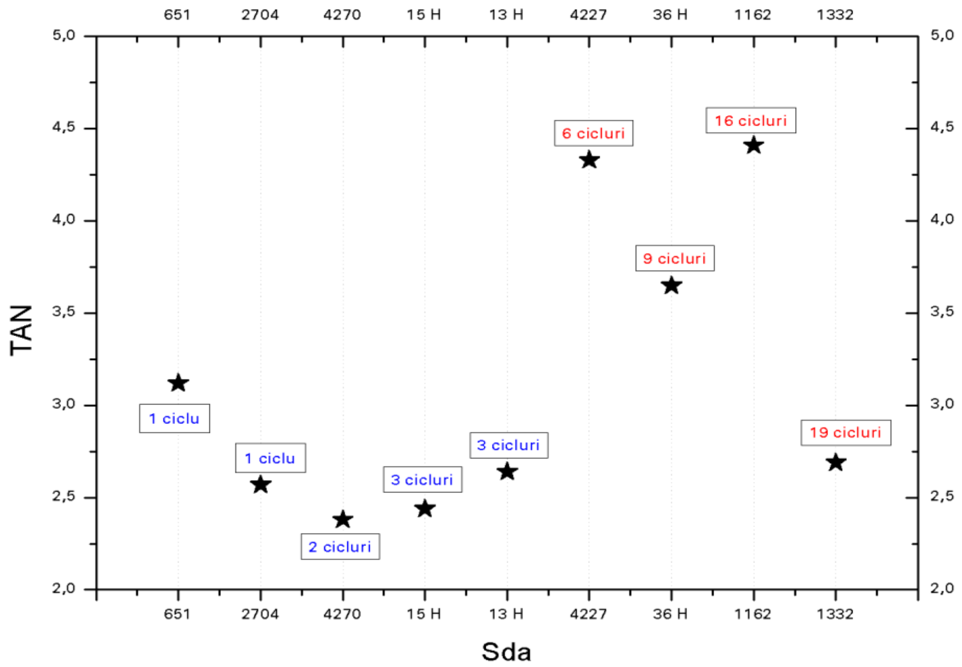

Fig. 3. Oil Displacement Profile

The study also highlighted the importance of aging duration and steam cycle optimization for maximizing recovery. Extended aging (7 months) improved oil displacement, particularly in high-permeability sand packs, confirming that thermal treatment duration influences pore-scale interactions. The inverse relationship between carbon residue and steam cycles suggests that prolonged thermal exposure upgrades oil quality, while rising acidity signals potential operational challenges. These findings align with field observations from Suplacu de Barcău, where cyclic steam stimulation (CSS) has historically boosted production. However, the non-linear benefits of additional steam cycles—where excessive cycling may not proportionally improve recovery—call for a balanced approach in thermal EOR design.

6. Conclusions

Thermal alteration significantly modifies the flow behavior and chemical properties of heavy crude oils. Higher steam cycling leads to reduced viscosity, improved permeability, and more efficient oil displacement under laboratory conditions. Physicochemical analyses showed that oil subjected to more steam cycles had lower residual carbon and higher TAN, reflecting ongoing degradation and upgrading processes. These results demonstrate that thermal simulation and displacement testing provide valuable insights for optimizing thermal EOR operations. The Suplacu field continues to respond positively to cyclic steam stimulation, and further tailored thermal treatments based on laboratory modeling can support increased recovery and reduced energy input.

The study confirms that thermal alteration through steam cycling enhances heavy oil recovery by reducing viscosity and residual carbon while improving permeability. However, the accompanying increase in acidity (TAN) underscores the need for corrosion management in field operations. Key takeaways include:

1. Optimal steam cycling improves displacement efficiency, but diminishing returns may occur beyond a certain cycle count, necessitating field-specific optimization.
2. Thermal cracking reduces coke formation, upgrading oil quality but also increasing reactivity, which may affect downstream processing.
3. Longer aging periods enhance recovery, suggesting that soak times in CSS operations should be carefully calibrated.

For Suplacu and similar fields, these findings support customized steam injection strategies that balance recovery gains with chemical degradation risks. Future work should explore hybrid EOR methods (e.g., steam with solvents or nano-fluids) to mitigate acidity while sustaining high recovery rates.

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