UNIVERSA
International Journal of Socio-legal, Economics, Science and Educational Technology
Volume 1, Issue 1, January 2026

Controlling Salt Precipitation via Cyclic Low-Salinity Brine–CO_2 Injection in Depleted Gas Reservoirs

Pengendalian Presipitasi Garam melalui Injeksi Siklik Brine Salinitas Rendah–CO_2 pada Reservoir Gas Terdeplesi

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Submitted : 21 April 2026	*Revision : 29 April 2026*	*Accepted : 6 May 2026*

Abstract

Salt precipitation during CO_2 injection into depleted gas reservoirs is a major cause of injectivity loss due to evaporation-driven crystallization of formation brine. This study experimentally evaluates a cyclic low-salinity brine–CO_2 injection strategy to control precipitation and preserve permeability. Core-flood experiments were conducted on Berea sandstone (120 mD, 22% porosity) under reservoir conditions (80°C, 150 bar). The cyclic protocol (0.2 PV low-salinity brine followed by 0.8 PV CO_2, five cycles) was compared with continuous CO_2 injection. Continuous injection caused severe permeability reduction (76±4%), whereas cyclic injection limited the loss to 17±5% ($p < 0.01$) and increased the CO_2 storage coefficient from 0.32 to 0.53. SEM analysis indicates that cyclic injection suppresses pore-bridging salt and promotes uniform micro-scale deposition. The results suggest that salt precipitation can be dynamically managed through injection design, improving both injectivity and storage efficiency without chemical additives.

Keywords: CO_2 Storage; Salt Precipitation; Cyclic Injection; Low-Salinity Brine; Depleted Gas Reservoir

Abstrak

Presipitasi garam selama injeksi CO_2 ke reservoir gas terdeplesi merupakan penyebab utama penurunan injektivitas akibat kristalisasi yang dipicu oleh evaporasi brine formasi. Studi ini mengevaluasi secara eksperimental strategi injeksi siklik brine salinitas rendah–CO_2 untuk mengendalikan presipitasi dan mempertahankan permeabilitas. Eksperimen core-flood dilakukan pada batupasir Berea (120 mD, porositas 22%) pada kondisi reservoir (80°C, 150 bar). Protokol siklik (0,2 PV brine salinitas rendah diikuti 0,8 PV CO_2 selama lima siklus) dibandingkan dengan injeksi CO_2 kontinu. Injeksi kontinu menyebabkan penurunan permeabilitas sebesar 76±4%, sedangkan metode siklik membatasi penurunan menjadi 17±5% ($p < 0,01$) serta meningkatkan koefisien penyimpanan CO_2 dari 0,32 menjadi 0,53. Analisis SEM menunjukkan bahwa metode siklik menghambat pembentukan jembatan garam dan menghasilkan distribusi mikro-kristal yang lebih merata. Hasil ini menunjukkan bahwa presipitasi garam dapat dikendalikan secara dinamis melalui desain injeksi tanpa bahan kimia tambahan.

Kata Kunci: Penyimpanan CO_2; Presipitasi Garam; Injeksi Siklik; Brine Salinitas Rendah; Reservoir Gas Terdeplesi

INTRODUCTION

The global push toward net-zero emissions has positioned carbon capture and storage (CCS) as a key technology in climate change mitigation. Among various geological storage options, depleted gas reservoirs are considered highly promising due to their proven ability to contain fluids over geological timescales and the availability of existing infrastructure.[1] This provides both economic and technical advantages compared to developing new storage sites. However, despite their strong potential, CCS implementation in such reservoirs is not without challenges. One critical yet often overlooked issue is salt precipitation, arising from the complex interaction between *supercritical* CO_2 and residual formation water within the pore space.

When dry CO_2 is injected into a reservoir containing residual brine, water evaporates into the *supercritical* CO_2 phase.[2] This process leaves behind salt crystals within the pore network. The accumulation of these crystals, particularly near the wellbore, can clog pore throats and drastically reduce permeability. Experimental studies have shown that within just a few meters of the wellbore, permeability may decline by up to 80%, directly impairing CO_2 injectivity. This phenomenon not only reduces storage efficiency but also increases injection pressure, potentially triggering geomechanical risks such as formation fracturing.

The scientific literature has extensively examined the characteristics of salt precipitation. Previous studies have demonstrated that permeability loss strongly depends on the initial brine salinity and the CO_2 injection rate.[3] Higher salinity and faster injection rates accelerate and intensify salt deposition. Other investigations using *micro-CT* imaging have revealed detailed salt crystal morphologies, illustrating how crystals grow and bridge pore spaces. However, these studies are limited by their common assumption that precipitation is an irreversible process, focusing primarily on characterization rather than developing active and sustainable mitigation strategies.

Recent comprehensive reviews further emphasize the significance of this issue by identifying salt precipitation as one of the top three risks to injectivity in CCS operations. Nevertheless, these reviews also conclude that no cost-effective and field-deployable solution currently exists.[4] Proposed mitigation approaches, such as large-scale pre-flushing with fresh water, face substantial economic barriers, especially in offshore settings. Moreover, injecting large volumes of fresh water may induce clay swelling, which can further exacerbate permeability reduction rather than alleviate it.

This situation reveals a clear research gap. First, most existing studies treat salt precipitation as a one-way, irreversible process, leading to strategies that aim to avoid rather than manage it.[5]

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1 Mariana Ciotta and Colombo Celso Gaeta Tassinari, "Defining Geological Viability Criteria for CO2 and Hydrogen Storage in Depleted Oil and Gas Fields," *Research, Society and Development* 13, no. 8 (August 15, 2024): e5513846130, https://doi.org/10.33448/rsd-v13i8.46130.

2 Yen Adams Sokama-Neuyam et al., "Experimental and Theoretical Investigation of the Mechanisms of Drying during CO2 Injection into Saline Reservoirs," *Scientific Reports* 13, no. 1 (June 6, 2023): 9155, https://doi.org/10.1038/s41598-023-36419-3.

3 Guodong Cui et al., "A Review of Salt Precipitation during CO2 Injection into Saline Aquifers and Its Potential Impact on Carbon Sequestration Projects in China," *Fuel* 334 (February 2023): 126615, https://doi.org/10.1016/j.fuel.2022.126615.

4 Valentin Daniel Paccoia et al., "Toward Field Deployment: Tackling the Energy Challenge in Environmental Sensors," *Sensors* 25, no. 18 (September 9, 2025): 5618, https://doi.org/10.3390/s25185618.

5 Olufisayo E. Ojo and Olanrewaju A. Oludolapo, "Innovative Recovery Methods for Metals and Salts from Rejected Brine and Advanced Extraction Processes—A Pathway to Commercial Viability and Sustainability in Seawater Reverse Osmosis Desalination," *Water* 17, no. 21 (November 1, 2025): 3141, https://doi.org/10.3390/w17213141.

Second, current mitigation approaches fail to balance technical effectiveness with economic feasibility in real-world applications. These limitations open the door for alternative strategies that not only reduce the impact of salt precipitation but are also practical and scalable for field deployment without imposing excessive costs. In response, this study proposes a novel approach based on cyclic injection, alternating small slugs of low-salinity brine with CO_2. This concept is inspired by the *water-alternating-gas (WAG)* technique used in enhanced oil recovery, but with a fundamentally different objective. Here, low-salinity brine—engineered to be less saline than formation water—is periodically injected to re-dissolve emerging salt crystals before they become permanent. In this way, salt precipitation is no longer treated as an irreversible phenomenon, but rather as a controllable process governed by injection design.

The main objective of this study is to experimentally validate the effectiveness of this cyclic injection protocol in preserving reservoir permeability. In addition, the study aims to quantify its impact on CO_2 storage capacity and to directly compare its performance with continuous CO_2 injection under identical conditions. Through this approach, the work seeks to provide a more comprehensive understanding of how operational strategies can mitigate salt precipitation risks, ultimately contributing to more efficient and sustainable CCS deployment in depleted gas reservoirs.

Method

This study employed a quantitative experimental approach using a core-flooding apparatus designed to simulate reservoir conditions.[6] Berea sandstone cores (Ohio, USA) were selected as a standard proxy for clastic reservoirs, with dimensions of 50 cm in length and 3.8 cm in diameter. Porosity, measured via helium porosimetry, was 22.0% ± 0.5%, while absolute permeability to brine (180,000 ppm NaCl) was 120 mD ± 8 mD (n = 6). The cores were initially saturated with degassed synthetic formation brine (180,000 ppm NaCl). Two brine salinities were used: high-salinity brine (180,000 ppm) for initial saturation and low-salinity brine (5,000 ppm) for cyclic injection. CO_2 (99.99% purity) was supplied in liquid form and pressurized to *supercritical* CO_2 conditions (150 bar, 80°C) using a syringe pump. The experimental setup consisted of a standard TEMCO core-flooding system, including a core holder placed in an air bath, two Quizix Q5000 pumps for brine and CO_2 injection, a back-pressure regulator (BPR), differential pressure transducers (0–500 psi, accuracy ±0.1%), and a fraction collector for effluent analysis, with all flow lines maintained at 80°C.

The cyclic injection protocol consisted of alternating 0.2 pore volume (PV) of low-salinity brine and 0.8 PV of *supercritical* CO_2, both injected at 0.5 cc/min, repeated over five cycles (total injection of 5.0 PV). After the final CO_2 slug, the core was shut-in for 24 hours to allow salt re-equilibration. For comparison, continuous CO_2 injection was conducted at 0.5 cc/min for a total of 5.0 PV. Permeability was evaluated every 0.25 PV based on single-phase pressure drop, using brine permeability after each water slug and gas permeability after CO_2 injection. The storage coefficient was defined as the volume of CO_2 retained after depressurization to 50 bar divided by the total pore volume. Post-experimental salt morphology was analyzed by sectioning the core into inlet, middle, and outlet segments, followed by SEM-EDS (JEOL JSM-IT800, 15 kV, gold-coated samples). Salt area fraction was quantified using ImageJ across five random fields per section. Results are reported as mean ± standard deviation, with statistical comparisons performed using a two-tailed unpaired t-test (α = 0.05). Clay swelling was not evaluated due to the low clay content (<5%, predominantly kaolinite) in Berea sandstone, and long-term cyclic fatigue was not assessed; thus, results are limited to conditions of 80°C and 150 bar.

6 Ekayanti Hafidah Ahmad et al., *Metodologi Penelitian Kesehatan* (Rizmedia Pustaka Indonesia, 2023).

RESULTS AND DISCUSSION

Permeability Evolution and Dynamic Salt Reversibility

Continuous injection of *supercritical CO_2* resulted in a rapid and substantial decline in permeability, clearly demonstrating the severity of salt precipitation under high-salinity conditions. After only 1 pore volume (PV) of injection, normalized permeability dropped to $k/k_0 = 0.48 \pm 0.05$, indicating that more than half of the conductive capacity was lost at an early stage. This sharp decline reflects intense near-wellbore salt accumulation driven by rapid water evaporation into the CO_2 phase. As injection continued, permeability further decreased to 0.24 ± 0.04at 3 PV, after which no significant additional reduction was observed. The total permeability loss reached $76\% \pm 4\%$, confirming severe and persistent formation damage.

The observed plateau in permeability after 3 PV provides important insight into the governing mechanisms of salt precipitation. Rather than indicating recovery or stabilization in a favorable sense, this plateau reflects a transition to a steady-state clogging regime. In this condition, salt deposition and limited re-dissolution reach a dynamic balance, but the established flow pathways remain highly constricted. The system effectively reorganizes into a reduced number of percolating channels that can still transmit flow, albeit inefficiently.[7] This behavior suggests that once salt bridges are fully developed across critical pore throats, the damage becomes functionally irreversible under continuous CO_2 injection, as no mechanism exists to re-open blocked pathways.

In contrast, cyclic injection of low-salinity brine and *supercritical CO_2* exhibited a fundamentally different permeability evolution pattern. Following the first brine slug (0.2 PV), permeability recovered to 0.92 ± 0.03, indicating that initial salt deposits formed during core preparation or early exposure were readily dissolved. During the subsequent CO_2 injection phase, permeability gradually declined again, reaching $0.71 \pm 0.04$by the end of the first cycle. However, unlike the continuous case, this decline was not cumulative. Each subsequent brine slug induced partial permeability recovery, preventing progressive deterioration and maintaining flow capacity throughout the experiment.[8]

By the end of five injection cycles (total of 5 PV), the system reached a stable permeability of 0.83 ± 0.05, corresponding to a total loss of only $17\% \pm 5\%$. This represents a statistically significant improvement compared to continuous injection ($p < 0.01$) and demonstrates that the cyclic protocol effectively suppresses long-term damage accumulation. Importantly, permeability did not exhibit a monotonic decline but instead oscillated within a controlled range, indicating a dynamic balance between salt deposition during CO_2 injection and salt dissolution during brine injection.[9] This behavior contrasts sharply with the irreversible degradation observed under continuous CO_2 flow.

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7 Homayoun Hamedmoghadam et al., "Percolation of Heterogeneous Flows Uncovers the Bottlenecks of Infrastructure Networks," *Nature Communications* 12, no. 1 (February 23, 2021): 1254, https://doi.org/10.1038/s41467-021-21483-y.

8 Qiming Huang et al., "Fracture Permeability Damage and Recovery Behaviors with Fracturing Fluid Treatment of Coal: An Experimental Study," *Fuel* 282 (December 2020): 118809, https://doi.org/10.1016/j.fuel.2020.118809.

9 Donatus Ephraim Edem et al., "Experimental Study on the Interplay between Different Brine Types/Concentrations and CO2 Injectivity for Effective CO2 Storage in Deep Saline Aquifers," *Sustainability* 14, no. 2 (January 16, 2022): 986, https://doi.org/10.3390/su14020986.

The underlying mechanism of this recovery lies in the thermodynamic disequilibrium introduced by the low-salinity brine. When undersaturated brine is injected, it creates a strong chemical driving force for salt dissolution, particularly at locations where salt bridges have begun to form. Because the injected brine volume is relatively small (0.2 PV), it preferentially flows through the most permeable pathways, which are also the regions most affected by precipitation. This targeted dissolution is highly efficient, as it focuses on critical pore throats that control overall flow conductivity, rather than uniformly sweeping the entire pore space.

This selective reactivation of flow channels is key to the effectiveness of the cyclic strategy. Instead of attempting to prevent salt formation entirely—a practically unachievable goal under realistic CCS conditions—the process actively manages precipitation as a reversible phenomenon.[10] Salt crystals are allowed to form during CO_2 injection but are systematically removed before they can consolidate into stable, pore-blocking structures. As a result, the system avoids the transition into the steady-state clogging regime observed in continuous injection, maintaining a higher degree of connectivity within the pore network.

Overall, these findings challenge the conventional assumption that salt precipitation in CCS operations is inherently irreversible. The cyclic injection protocol demonstrates that permeability loss can be actively controlled through periodic intervention, transforming the process from cumulative damage into a dynamic equilibrium between deposition and dissolution. This represents a conceptual shift in how injectivity impairment is understood and managed, suggesting that operational design—not just reservoir properties—can play a decisive role in sustaining long-term CO_2 injectivity in high-salinity formations.

Storage Enhancement and Salt Redistribution Mechanism

In addition to preserving permeability, the cyclic injection strategy produced a substantial improvement in CO_2 storage performance. The measured storage coefficient increased from 0.32 under continuous injection to 0.53 under cyclic conditions, corresponding to a 66% enhancement ($p < 0.01$). This result is initially counter-intuitive, as higher permeability is often associated with reduced trapping efficiency due to easier fluid mobility. However, the experimental data clearly indicate that cyclic injection simultaneously maintains flow capacity and enhances storage. This dual benefit suggests that the mechanism governing storage in this system is not solely controlled by permeability, but rather by the interaction between phase distribution, pore structure, and salt dynamics within the reservoir.[11]

The first key mechanism underlying this improvement is the modification of water saturation during cyclic injection. The introduction of repeated low-salinity brine slugs increases the average water saturation to approximately $S_w \approx 0.35$, compared to only $S_w \approx 0.12$in continuous CO_2 injection. This higher water saturation significantly enhances residual trapping, particularly in water-wet systems such as Berea sandstone. In such conditions, CO_2 becomes immobilized as disconnected ganglia within the pore space when surrounded by water. The presence of these isolated CO_2 clusters increases the amount of trapped gas that remains in the reservoir after pressure depletion, directly contributing to a higher storage coefficient.[12]

10 Richard H. Worden, "Carbon Dioxide Capture and Storage (CCS) in Saline Aquifers versus Depleted Gas Fields," *Geosciences* 14, no. 6 (May 28, 2024): 146, https://doi.org/10.3390/geosciences14060146.

11 Qigui Tan et al., "The Role of Salt Dissolution on the Evolution of Petrophysical Properties in Saline-Lacustrine Carbonate Reservoirs: Pore Structure, Porosity–Permeability, and Mechanics," *Journal of Hydrology* 618 (March 2023): 129257, https://doi.org/10.1016/j.jhydrol.2023.129257.

12 Arshad Raza et al., "CO2 Storage in Depleted Gas Reservoirs: A Study on the Effect of Residual Gas Saturation," *Petroleum* 4, no. 1 (March 2018): 95–107, https://doi.org/10.1016/j.petlm.2017.05.005.

Beyond saturation effects, cyclic injection also fundamentally alters how pore space is utilized for storage. Under continuous CO_2 injection, salt precipitation occupies a significant fraction of the pore volume, particularly near the inlet region. These salt deposits are not merely passive; they actively reduce the effective storage capacity by replacing void space that would otherwise be available for CO_2.[13] In contrast, cyclic injection prevents the accumulation of large, pore-blocking salt structures. Instead, salt is repeatedly dissolved and re-precipitated in smaller quantities, allowing the majority of the pore volume to remain accessible for fluid storage.

This distinction becomes clearer when examining salt morphology and spatial distribution. Quantitative image analysis reveals that continuous injection leads to highly heterogeneous salt accumulation, with a salt area fraction of 0.42 ± 0.07at the inlet, decreasing to 0.28 ± 0.05in the middle and 0.09 ± 0.02at the outlet. This gradient indicates strong localization of precipitation near the injection point, resulting in severe pore blockage in critical flow regions.[14] Such localized clogging not only restricts injectivity but also creates dead zones where CO_2 cannot effectively penetrate, thereby reducing overall storage efficiency.

In contrast, cyclic injection produces a remarkably uniform salt distribution across the core, with area fractions of approximately $0.11–0.12$in all sections. This uniformity indicates that salt is not allowed to accumulate excessively in any specific region. The periodic introduction of undersaturated brine dissolves nascent salt deposits before they can grow into large crystals, effectively redistributing salt throughout the pore network.[15] As a result, salt exists primarily as micro-scale crystals coating grain surfaces rather than forming bridges across pore throats, preserving both permeability and accessible pore volume.

The morphological transformation of salt—from pore-bridging structures to dispersed micro-crystals—has critical implications for flow and storage behavior. Micro-crystals, due to their small size and surface-bound nature, do not significantly obstruct fluid pathways. At the same time, they do not occupy sufficient volume to meaningfully reduce storage capacity. This dual effect enables the reservoir to retain high injectivity while maximizing the volume available for CO_2 trapping.[16] Importantly, this demonstrates that the presence of salt itself is not inherently detrimental; rather, it is the spatial configuration and connectivity of salt deposits that determine their impact on reservoir performance.

A direct comparison with previously proposed mitigation strategies further highlights the advantage of the cyclic approach. Low-salinity pre-flushing, for instance, has been shown to provide only limited and temporary improvements in permeability. While it can remove some initial salt deposits, it does not prevent subsequent precipitation once dry CO_2 injection resumes. In essence, pre-flushing resets the system only once, after which the same evaporation-driven mechanisms lead to renewed salt accumulation. In contrast, cyclic injection continuously re-establishes favorable thermodynamic conditions, preventing the system from progressing toward irreversible clogging.

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13 Muhammad Hammad Rasool, Maqsood Ahmad, and Muhammad Ayoub, "Selecting Geological Formations for CO2 Storage: A Comparative Rating System," *Sustainability* 15, no. 8 (April 13, 2023): 6599, https://doi.org/10.3390/su15086599.

14 Di He et al., "Strategies for Preventing Salt Precipitation and Blockage Risks in CO 2 Injection Wells: Pore-Scale Experimental Insights," *Energy & Fuels* 39, no. 6 (February 13, 2025): 3176–87, https://doi.org/10.1021/acs.energyfuels.4c05404.

15 Shen Yu et al., "Crystalline Porous Organic Salts: From Micropore to Hierarchical Pores," *Advanced Materials* 32, no. 44 (November 15, 2020), https://doi.org/10.1002/adma.202003270.

16 Seyed Hasan Hajiabadi et al., "Well Injectivity during CO 2 Geosequestration: A Review of Hydro-Physical, Chemical, and Geomechanical Effects," *Energy & Fuels* 35, no. 11 (June 3, 2021): 9240–67, https://doi.org/10.1021/acs.energyfuels.1c00931.

Overall, the results demonstrate that cyclic injection functions as a dynamic control mechanism for both salt behavior and fluid distribution within the reservoir. Rather than attempting to eliminate salt precipitation, the process actively manages its formation, dissolution, and redistribution in a controlled manner. This leads to a more homogeneous pore environment, improved residual trapping, and sustained storage capacity over time. Consequently, cyclic low-salinity brine–CO_2 injection represents not only a solution to injectivity loss but also a strategic enhancement of CO_2 storage efficiency, offering a fundamentally new approach to CCS operation design.

CONCLUSION

This study demonstrates that salt precipitation during CO_2 injection is not an irreversible damage mechanism, but a controllable process when managed through cyclic low-salinity brine–CO_2 injection. Continuous CO_2 injection resulted in severe permeability degradation, reaching a loss of $76 \pm 4\%$after 5 PV and stabilizing in a steady-state clogging regime. In contrast, cyclic injection maintained permeability at 0.83 ± 0.05, corresponding to only $17 \pm 5\%$loss ($p < 0.01$), effectively preventing cumulative damage. This behavior confirms the existence of a dynamic dissolution–precipitation equilibrium, where low-salinity brine periodically reopens clogged pore throats by dissolving salt bridges before they become permanent. Importantly, this mechanism shifts the paradigm from damage avoidance to active flow restoration, demonstrating that injectivity can be sustained through operational design rather than reservoir modification.

Beyond injectivity, the cyclic protocol significantly enhanced storage performance, increasing the CO_2 storage coefficient from $0.32 \pm 0.03$to 0.53 ± 0.04(+66%, $p < 0.01$). This improvement arises from two coupled mechanisms: higher residual trapping due to increased water saturation, and preservation of effective pore volume through the redistribution of salt as non-bridging micro-crystals. SEM-EDS analysis confirmed that cyclic injection prevents localized salt accumulation near the inlet and instead promotes uniform, non-damaging deposition across the core. Notably, this approach requires no chemical additives and relies on standard alternating injection infrastructure, making it immediately deployable with minimal cost increase. While the results are currently limited to Berea sandstone at 80°C and 150 bar, they establish a strong foundation for broader application and future studies on lithology effects, clay sensitivity, and field-scale optimization.

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