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Invited Review

Carbon dioxide storage in saline aquifers: A comprehensive review

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Abstract:
Deep saline aquifers are widely regarded as the most promising media for large-scale CO_2 storage due to their extensive distribution and enormous capacity. However, existing studies have largely focused on individual trapping mechanisms or static assessments, leaving a gap in systematic integration of multi-mechanism coupled evolution and intelligent synergistic storage pathways. This work provides a comprehensive review covering four core dimensions: Storage mechanisms, storage conditions, storage potential assessment methods, and key emerging technologies. The findings indicate that CO_2 storage involves synergistic evolution of structural, residual, dissolution, and mineral trapping, with efficiency critically governed by caprock sealing integrity and coupled wettability-salinity-temperature effects. For storage potential, this study summarizes various methods for calculating the potential of multiple storage mechanisms. Regarding technologies, the dual functions of microbially induced carbonate precipitation in leakage sealing and mineralization enhancement are reviewed, alongside microfluidics and artificial intelligence for pore-scale characterization and real-time monitoring. Drawing on global projects, this study analyzes challenges including high costs, leakage risks, and induced seismicity, and establishes an integrated framework combining offshore storage, microbially induced carbonate precipitation biomineralization, and artificial intelligent monitoring. This framework signifies a paradigm shift from passive geological containment toward bio-intelligent active regulation, offering a systematic pathway for large-scale, intelligent carbon storage in saline aquifers.

1. Introduction

Geological CO_2 storage in saline aquifers is a key pathway for addressing climate change and achieving carbon sequestration. Among geological carbon storage options, deep saline aquifers are considered the most promising sites for large-scale CO_2 emission reduction because of their widespread distribution and enormous storage capacity (Dechezleprêtre et al., 2025; Izadpanahi et al., 2024; Simonsen et al., 2024). Their global theoretical capacity is estimated to be hundreds of billions to trillions of tonnes, far exceeding the capacities of depleted hydrocarbon reservoirs and coal seams (Worden, 2024; Helmi et al., 2025; Mazhar et al., 2026). Consequently, they constitute a pivotal medium for permanent CO_2 sequestration and long-term atmospheric isolation at the terminal stage of the carbon capture, utilization, and storage (CCUS) framework (Choe et al., 2023; Davarpanah, 2024; Helmi et al., 2025). Un-

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like oil and gas reservoirs or coal seams, saline aquifers do not depend on hydrocarbon reservoir geology or coal adsorption characteristics (Massarweh and Abushaikha, 2024). Therefore, they can store CO_2 captured from diverse sources, including fossil fuel power plants, industrial facilities, and bioenergy systems (Al-Shargabi et al., 2022; Sambo et al., 2023; Bashir et al., 2024). Currently, multiple field-scale demonstration projects have been implemented worldwide, including the Sleipner project in Norway and the In Salah project in Algeria (Tanase and Tanaka, 2021; Izadian, 2024; Mei et al., 2025). Collectively, these projects have confirmed the technical viability of geological CO_2 storage in saline aquifers. As the demand for large-scale carbon sequestration grows, saline aquifer storage is increasingly being integrated with several frontier approaches. These include microbially induced carbonate precipitation (MICP) for accelerating permanent CO_2 immobilization (Xiao et al., 2024; Nixon et al., 2025), microfluidic platforms for *in-situ* simulation of pore-scale migration (Xiao et al., 2024; Zhong et al., 2026), and artificial intelligence (AI) for optimizing injection protocols and risk evaluation (Lin et al., 2025; Aminaho et al., 2026; Yang et al., 2026). Their integration is shifting full-lifecycle storage operations from empirically driven practices to intelligent, synergistically coordinated decision-making frameworks.

Saline aquifers are extensively developed within sedimentary basins worldwide, exhibiting high porosity, reasonable permeability, and relatively competent caprock integrity, which collectively render them as ideal repositories for CO_2 storage. Following the injection of CO_2 into saline aquifers, the sequestration process entails the synergistic interplay and coupling of various trapping mechanisms, namely structural trapping, residual trapping, dissolution trapping, and mineral trapping (Golding et al., 2011; Sampath et al., 2019; Izadpanahi et al., 2024). The sequential interplay and synergistic coordination of various trapping mechanisms over distinct temporal scales underpin the theoretical framework of CO_2 geological storage in saline aquifers, thereby conferring upon it the potential to achieve long-term and secure containment (Ranathunga et al., 2014; Jafari et al., 2017).

However, key knowledge gaps still exist in understanding CO_2 storage in saline aquifers. One is the lack of a unified analytical framework for the temporal evolution and multi-mechanism coupling of storage processes. For instance, the Snøhvit project achieved only 10% of its expected injection volume because pore-structure constraints on residual trapping were underestimated (Hansen et al., 2013; Singh et al., 2025). Another is the insufficient understanding of the synergistic effects of multiple storage-condition factors, as seen in the Sleipner project, where inadequate early assessment of overburden heterogeneity and fracture systems caused injected CO_2 to deviate from the intended reservoir (Zhang et al., 2017; Izadian, 2024; Yang et al., 2025).

This study systematically reviews CO_2 storage in saline aquifers across mechanisms, conditions, assessment methods, and technologies, supported by global case studies (Table 1). Multi-mechanism coupling and temporal evolution of trapping processes are elucidated, alongside synergistic effects of caprock integrity and wettability-salinity-temperature on storage efficiency. This study summarizes methods for evaluating multiple storage mechanisms. The dual functions of MICP in leakage sealing and mineralization enhancement are examined, along with microfluidics and AI applications. Key challenges are evaluated, and an integrated offshore-MICP-AI framework is established, offering a systematic pathway toward bio-intelligent active regulation for large-scale carbon storage.

2. Review methods

This systematic literature review involved literature retrieval, screening, and integrative analysis. It focused on reservoir suitability, storage capacity assessment, long-term migration behavior, and coupled geochemical-mechanical mechanisms governing geological CO_2 storage in deep saline aquifers (Fig. S1; Page et al., 2021). The literature was searched primarily through Web of Science, Google Scholar, and Scopus using eight selected keywords. The initial searches yielded approximately 6,840 records from Web of Science, 5,753 from Google Scholar, and 9,121 from Scopus. Publications from the past five years represented approximately 38.6%-47.3% of these records, reflecting the rapid development of the field within the broader context of carbon neutrality. Targeted searches of representative case study areas identified 2,154, 1,985, 3,204, and 1,467 relevant publications, respectively. Relatively complete geological datasets were available for all four areas.

This review employed a two-stage screening process: (1) Initial screening based on titles and abstracts and (2) full-text assessment followed by classification according to core themes. Articles meeting any of the following criteria were excluded:

1) Studies targeting only hydrocarbon reservoirs or coalbed methane storage rather than saline aquifer storage;
2) Studies addressing shallow freshwater aquifers or surface water systems without involving deep supercritical conditions;
3) Studies based solely on idealized numerical simulations without calibration against experimental or field data;
4) Studies relying exclusively on laboratory batch experiments without extending to reservoir-scale or field-scale discussions;
5) Studies limited to pure diffusion or natural convection without analysis of injection-induced pressure and flow fields;
6) Studies involving CO_2-enhanced oil recovery or CO_2-enhanced gas recovery that are unrelated to the long-term security of geological storage;
7) Articles providing only regional tectonic descriptions without quantitative assessments of reservoir properties, mineral composition, or storage efficiency.

During the research process, a dynamic literature updating mechanism was established to ensure the continuous incorporation of the latest research findings into the integrated analysis. Detailed methodological descriptions are provided in the Supplementary Materials (Table S1).

Table 1. Major CO_2 storage projects in saline aquifers worldwide.

No.	Name	Injection time (a)	Location	Structural characteristics	Injection interval	Depth (m)	References
1	Sleipner	1996	North Sea, Norway	Fault-free with interbeds	Utsira formation	800	Izadian (2024)
2	In Salah	2004	Central Algeria	Gentle anticline	Tournaisian sandstone	1,880	Verdon et al. (2013)
3	Snøhvit	2008	Hammerfest Basin	Elongated EW-trending fault block system	The Tubåen formation	2,600	Trémosa et al. (2014)
4	Guoneng	2011	Ordos Basin	Monoclinic structure, faults not developed	Multiple aquifers	1,600-2,450	Li et al. (2016)
5	Otway	2007-2020	Southern Australia	No obvious structural trap	Upper Cretaceous Paaratte formation	1,128-1,528	Sharma et al. (2011)
6	Tomakomai	2016	Hokkaido, Japan	Anticlinal structure	Moebetsu sandstone formation	1,100-1,300, 2,400-3,000	Tanase and Tanaka (2021)
7	Gorgon	2019	Offshore Western Australia	Anticlinal structure	Dupuy deep reservoir formation	2,000-2,500	Flett et al. (2009)
8	Quest	2015	Alberta, Canada	Sandstone-type trap	Basal Cambrian sandstone	2,000	Harvey et al. (2022)
9	En ping 15-1	2021	South China Sea	A self-trapping structure	Dome-shaped saline aquifer	800	Ye et al. (2023)
10	Decatur	2011	Decatur, Illinois, USA	Good secondary porosity	Lower Mount Simon sandstone formation	2,129-2,149	Finley (2014)
11	Northern Lights	2024	Norwegian North Sea	No obvious structural trap	2,500 m below seabed	2,500	Griffiths et al. (2025)
12	CStorel	2014	Offshore Western Australia	Anticlinal structure	Jurassic formation	2,000-3,000	Cha (2024)

3. Storage mechanisms

CO_2 storage in saline aquifers involves several trapping mechanisms (Table 2), including structural, residual, dissolution, and mineral trapping (Fig. 1). These mechanisms can be divided into physical and chemical storage processes.

Structural and residual trapping are physical processes. Structural trapping occurs depends on the reservoir-caprock system (Ren et al., 2021; Luo et al., 2022). High-porosity and high-permeability saline aquifers provide storage space, whereas overlying low-permeability caprock limits upward CO_2 migration (Ringrose et al., 2021; Cui et al., 2023). Residual trapping is controlled by the pore-scale flow behavior (Jiang et al., 2026). Differences in surface tension and wettability between CO_2 and brine generate capillary pressure, which immobilizes part of the CO_2 and restricts its migration.

Dissolution and mineral trapping are the two primary geochemical immobilization mechanisms. They typically develop more slowly but provide increasingly stable storage over geological timescales (Riaz and Cinar, 2014; Xu et al., 2017). During dissolution trapping, pressure and concentration gradients drive CO_2 into the formation brine, and the resulting dissolved CO_2 increases brine density and acidity, which can promote convective mixing and initiate mineral reactions (Zhang et al., 2019; Liu et al., 2024). Mineral trapping occurs when dissolved CO_2-derived carbonate species react with available cations and rock minerals to precipitate stable carbonate phases (Bello et al., 2024; Yin et al., 2025). Their rates depend on fluid mixing, injection history, salinity, mineral availability, and reactive transport.

Dynamic coupling among the four primary trapping mechanisms can produce either reinforcing or constraining feedback. An increase in brine density following dissolution can initiate convection and accelerate further dissolution, provided that density contrast, permeability, and interfacial renewal are sufficient (Alhosani et al., 2020; Wang et al., 2025a). By

Table 2. Mechanisms of CO_2 storage in saline aquifers.

Mechanism	Principle	Precautions	References
Structural trapping	Depends on the physical structure of the formation.	The formation should be leak-tight, depending on the integrity of the caprock.	Riaz and Cinar (2014)
Residual trapping	Depends on the principles of wettability and capillary pressure.	CO_2 is trapped in small pores due to the presence of the wetting phase (brine).	Al Hameli et al. (2022)
Dissolution trapping	Depends on the affinity of brine for dissolving CO_2.	Controlled by temperature, pressure, rock type, salinity, and pH, thereby removing the buoyancy that arises from a separate CO_2 phase.	Riaz and Cinar (2014)
Mineral trapping	Relies on chemical reactions between the formation and fluids to form stable minerals.	Temperature and pressure enhance mineral trapping, subject to the influence of mineralogy.	Bello et al. (2024)
Adsorption trapping	CO_2 gas molecules are adsorbed onto solid rock surfaces via van der Waals forces or chemical bonds.	These storage methods utilize efficient storage systems, thereby reducing the potential for CO_2 plume migration within the reservoir.	Bello et al. (2024)
Ion exchange trapping	The presence of dissolved CO_2 causes ion exchange with minerals, thereby generating carbon-bearing ions.	Common in carbonate rock formations, the altered chemical environment may affect various trapping methods due to changes in their composition.	Al Hameli et al. (2022)
Hydrodynamic trapping	Combine physical trapping with chemical methods, using slowly migrating CO_2.	When formation water rises due to buoyancy, CO_2 pushes it in different directions, and then the remaining CO_2 is trapped in residual traps and structural or stratigraphic traps.	Al Hameli et al. (2022)

consuming dissolved carbon, mineral precipitation can sustain further dissolution when reactive cations, accessible mineral surfaces, and transport pathways remain available (Cicha-Szot et al., 2025). Conversely, residual trapping can isolate CO_2, reduce effective contact between gas and water, and lower mass-transfer efficiency. Reported reductions in dissolution rates range from 30% to 50% (Kaszuba et al., 2013). Mineral precipitation can narrow pore throats, impair permeability and injectivity, and restrict access to fresh reactive surfaces (Cicha-Szot et al., 2025; Ye et al., 2025). Thus, the net feedback is conditional rather than universally positive. It is jointly controlled by reservoir heterogeneity, injection rate and pressure history, pore-throat architecture, wettability, salinity, mineralogy, pH, and temperature. Positive coupling predominates where phase contact and reactive transport remain sufficient, whereas transport limitations, pore blockage, or loss of connectivity favor negative feedback.

4. Storage conditions

4.1 Caprock sealing capacity

Caprock sealing capacity is commonly evaluated using three interrelated components: Sealing ability, sealing geometry, and sealing integrity. These components have been widely investigated in previous studies on caprock sealing capacity (Iglauer et al., 2015; Raza et al., 2022; Zhang et al., 2025b).

Current studies on caprock sealing capacity in saline aquifers mainly examine two effects: Stress-field changes induced by CO_2 injection and geochemical alteration caused by CO_2-brine-rock interactions. In terms of sealing ability, in the Australian South-West Hub project, short-term mineral dissolution dominated after CO_2 injection (Jayasekara et al., 2020; Lu et al., 2025). The concentrations of Ca^{2+}, Mg^{2+}, and K^+ increase over time, enlarging the caprock pore volume and reducing the caprock sealing capacity (Hu et al., 2014; Mouallem et al., 2025). In terms of sealing integrity, in the In Salah project, CO_2 injection into thin, low-permeability sandstone changed the stress field and produced approximately 5 mm of surface uplift. Additionally, pressure buildup increases the possibility of caprock fracturing (Verdon et al., 2013; Hu et al., 2023). These studies have revealed, from various dimensions, the potential impacts of CO_2 injection on the three evaluation indicators of caprock sealing integrity.

4.2 Wettability-salinity-temperature coupled effects

In CO_2-water-rock systems, wettability ranges from strongly water-wet to strongly CO_2-wet conditions. Its evolution is essentially the result of the coupled effects of temperature, salinity, and interfacial tension (Arif et al., 2019; Al-Yaseri et al., 2021). Wettability controls the fluid distribution in porous media and affects residual saturation, capillary

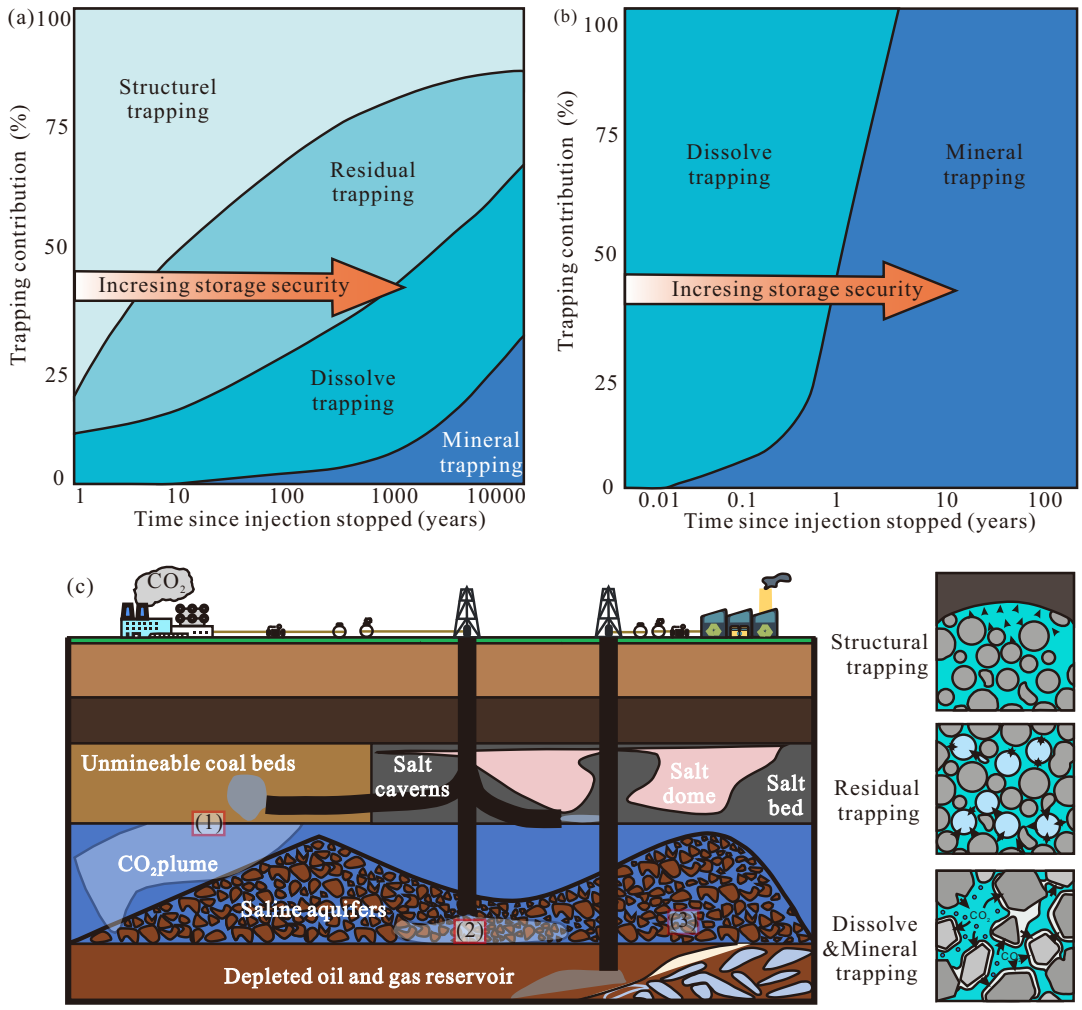


Fig. 1. CO_2 storage mechanisms in saline aquifers. (a) Trap contribution of CO_2 for each trap mechanism with time in a sedimentary basin (Snæbjörnsdóttir et al., 2020), (b) trap contribution of CO_2 for mineralization mechanism with time in a sedimentary basin (Raza et al., 2022) and (c) CCS procedure and CO_2 trap mechanism (Kim et al., 2023).

pressure, and relative permeability (Hu et al., 2015; Li et al., 2026a). At a given saturation, higher wettability reduces the brine relative permeability but increases the CO_2 relative permeability (Coelho et al., 2025). For a CO_2-water-rock system in which brine contacts a homogeneous rock surface, the Young-Dupré equation describes the relationship between the ideal contact angle and interfacial tension (Tokunaga and Wan, 2013).

According to the Young-Dupré equation, the contact angle is governed by the interfacial tension between the aqueous phase and CO_2. Within this relationship, salinity and temperature are the most active environmental variables that regulate interfacial tension and, consequently, wettability. Increasing salinity raises the brine-CO_2 interfacial tension, which tends to increase the contact angle and reduce water wettability (Al-Yaseri et al., 2016; Alnili et al., 2018; Dehury and Sangwai, 2025). Conversely, it lowers CO_2 solubility and changes both ionic activity in solution and the surface charge state of minerals (Jung and Wan, 2012; Wei et al., 2024). The coupling of these effects produces a non-monotonic wettability response to salinity. Some studies have reported that brine-CO_2 interfacial tension increases with salinity (Yekeen et al., 2021; Mirzaei-Paiaman and Okuno, 2024). However, others have observed no clear trend or only weak dependence on salinity. This discrepancy shows that salinity must be evaluated together with temperature and mineral type. During CO_2 storage in saline aquifers, temperature affects mineral, dissolution, and capillary trapping (Alhammad et al., 2023; Zhang, 2025). Higher temperatures promote CO_2 mineralization, with the mineralization rate increasing exponentially as temperature rises. This enhancement is more pronounced under mixed-wet conditions because direct CO_2-rock contact accelerates acidification, mineral dissolution, and carbonate precipitation (Shi et al., 2025; Khoramian et al., 2026).

Overall, wettability, temperature, and salinity are not independent controlling factors; rather, they are tightly interlocked through the chain of "interfacial tension-solubility-reaction rate". Salinity modulates interfacial potential energy and CO_2 phase behavior, and temperature governs reaction activation energy and fluid physical properties (Fig. 2).

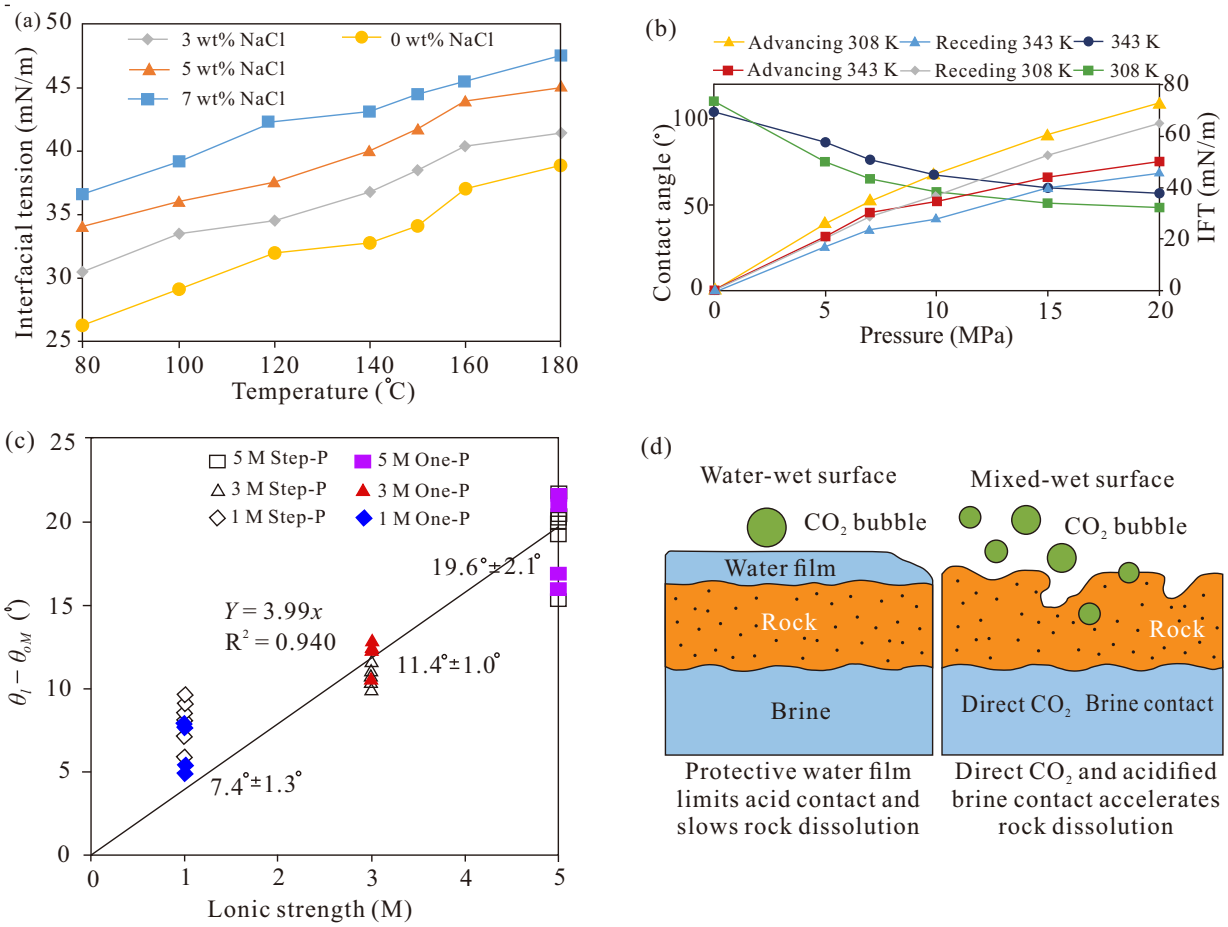


Fig. 2. Effects of salinity, temperature, and wettability on CO_2 trapping. (a) Effects of temperature and salinity on CO_2-brine interfacial tension (Yekeen et al., 2021), (b) advancing and receding contact angles in CO_2-brine-mica systems (Arif et al., 2016), (c) effect of ionic strength on silica contact angle (Arif et al., 2016) and (d) effects of temperature and wettability on CO2 mineralization (Khoramian et al., 2026).

5. Storage potential

Methods for assessing the geological CO_2 storage potential of saline aquifers are primarily based on the four trapping mechanisms introduced in Section 3. Accordingly, each mechanism is evaluated differently. Structural trapping capacity is generally estimated using the effective volume method (Goodman et al., 2011). Residual trapping capacity is determined by the residual gas trapping method (Ye et al., 2023; Yan et al., 2025). Solubility trapping capacity is calculated from the amount of gas dissolved in the aqueous phase, as determined using a solubility model (Bachu et al., 2007; Li et al., 2026b). Mineral trapping capacity is estimated by quantifying carbonate precipitation through reactive transport modeling or calculations based on mineralogical parameters (Goldberg et al., 2008).

The effective volume method assesses static storage within structural or stratigraphic traps by treating CO_2 storage as the occupation of pore space by free gas (Goodman et al., 2011; Saia et al., 2022). The corresponding equation is as follows:

$$M_{CO_2} = \rho_{CO_2} A_{st} h \phi E \quad (1)$$

where M_{CO_2} is the estimated CO_2 storage mass; ρ_{CO_2} is the density of CO_2 under reservoir conditions; and A_{st}, h, and ϕ denote the area of the structural or stratigraphic trap, effective thickness, and porosity, respectively, with E representing the storage efficiency factor.

The residual trapping method considers trapping after CO_2 plume migration. As water re-invades the pore space, residual gas forms, and a portion of the CO_2 remains trapped (Ye et al., 2023). where residual gas is formed when water re-invades the pore space and leaves a portion of CO_2 trapped. The corresponding equations are as follows:

$$V_s = \phi \Delta V_t S_t \quad (2)$$

$$M_r = \rho_{CO_2} V_s \quad (3)$$

where V_s is the volume of residually trapped CO_2; ΔV_t is the volume of rock that is invaded by water after being saturated with CO_2; and S_t is the residual gas saturation, M_r is the corresponding mass of residually trapped CO_2.

The solubility trapping method is based on CO_2 dissolution in formation water and is applicable to basin- and regional-scale assessments (Bachu et al., 2007). The corresponding equation is as follows:

$$M_b = A_{so} h \phi C \rho_w \Delta X_C \quad (4)$$

where M_b is the theoretical mass of storable CO_2; A_{so} is the area of the saline aquifer considered for solubility trapping; ΔX_C is the increment in CO_2 mass fraction; ρ_w is the density of formation water; and C is the comprehensive coefficient.

The pore-filling method estimates carbon storage potential by calculating the volume of rock pore space occupied by mineral precipitates generated through CO_2 mineralization (Goldberg et al., 2008; Gislason et al., 2010). The corresponding equation is as follows:

$$M_m = \gamma V \phi d \rho_m \beta \quad (5)$$

where M_m is the theoretical mass of storable CO_2; γ is the percentage of permeable layer thickness relative to the total formation thickness, V is the bulk volume of the storage formation; d is the mass percentage of CO_2 in the infilling material; ρ_m is the density of the infilling material; and β is the percentage of pore space occupied by the infilling material.

Saline aquifer CO_2 storage capacity is assessed through four trapping mechanisms: Structural, residual, solubility, and mineral trapping. These methods quantify storage based on available pore volume, residual gas saturation, CO_2 dissolution in formation water, and pore space occupied by mineral precipitates, respectively.

6. Emerging technologies

6.1 MICP

MICP refers to a biomineralization process in which specific microorganisms induce calcium carbonate precipitation through metabolic activity. Because of its environmental compatibility, MICP has potential applications in carbon sequestration and pollution remediation (Nixon et al., 2025). If CO_2 leaks from saline aquifers into groundwater, metal ions may be mobilized before carbon mineralization occurs (Liu et al., 2025). This process can contaminate groundwater and increase the concentrations of Ni, Al, Cr, Fe, and Mn to harmful levels for humans and biota (Rajasekar et al., 2021). MICP has been shown to convert divalent heavy metal ions, including Pb^{2+}, Cd^{2+}, and Cu^{2+}, into stable carbonate precipitates (Wei et al., 2025). The reaction principle is as follows:

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{Urease}} 2NH_4^+ + CO_3^{2-} \quad (6)$$

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3\downarrow \quad (7)$$

The carbonate precipitates generated by this process can also fill pores or fractures (Rajasekar et al., 2021).

6.2 Microfluidics

Microfluidic studies of geological CO_2 storage in saline aquifers primarily investigate trapping mechanisms, salt precipitation, and CO_2-water-rock interactions (Massarweh and Abushaikha, 2024; Cai et al., 2026; Zhong et al., 2026). By combining direct visualization with a high degree of experimental control, microfluidics has elucidated several microscopic mechanisms governing CO_2 storage in these formations (Dong et al., 2022; Cai et al., 2026). Microfluidics directly distinguishes phase states associated with structural and residual trapping and reveals how pore structure, roughness, and intermediate wetting conditions control residual trapping (Zhong et al., 2026). Microfluidic observations have revealed, for the first time, two distinct salt crystallization modes: Blocky and polycrystalline aggregation (Riaz and Cinar, 2014). They have also clarified how salinity and low injection rates promote crystallization and how crystallization contributes to both injection damage and fracture sealing (Riaz and Cinar, 2014). Although chip materials impose limitations, microfluidic systems can still effectively capture carbonate dissolution and pore evolution during CO_2-water-rock reactions (Massarweh and Abushaikha, 2024).

6.3 AI

AI supports geological CO_2 storage in saline aquifers across three main areas: Site screening and characterization, dynamic simulation and prediction, and real-time monitoring and integrity assessment. For site screening and characterization, deep learning automates the interpretation of three-dimensional seismic data, significantly improving the efficiency and accuracy of geological modeling (Aminaho et al., 2026; Yang et al., 2026). For dynamic simulation and prediction, AI surrogate models offer faster alternatives to numerical simulators, reducing computation time by several orders of magnitude. These models enable high-resolution, real-time predictions of how CO_2 plumes evolve in space and time. For real-time monitoring and integrity assessment, AI recasts four-dimensional seismic analysis as a computer vision task. Models such as Vision Transformers automatically segment CO_2 plumes and detect weak leakage signals (Chen et al., 2023; Yang et al., 2026). AI also uses time-series pressure monitoring to issue early warnings of anomalies (Carrascal-Hernández et al., 2025; Wu et al., 2026). By classifying sonic log images and processing distributed fiber-optic sensing data, it automates assessments of the mechanical integrity of wellbore cement sheaths and caprock (Carrascal-Hernández et al., 2025; Wu et al., 2026).

7. Typical case analysis

Saline aquifer carbon storage projects have been implemented globally. The representative projects examined here illustrate the current state of development and provide a basis for comparing geological settings, injection schemes, and monitoring results (Fig. 3).

7.1 Sleipner project, Norway

The Sleipner project in Norway represents one of the earliest and most influential demonstrations of CO_2 storage in saline aquifers (Torp and Gale, 2004). The project began in 1996 in the Norwegian North Sea. Its main purpose was to process natural gas from the Sleipner Vest gas field, where the CO_2 content is approximately 9%, exceeding the market limit of less than 2.5% (Torp and Gale, 2004). After separation and treatment, the captured CO_2 is injected through a dedicated deviated well into the Utsira sandstone saline aquifer, 800 m below the seabed. The stable pore structure and strong

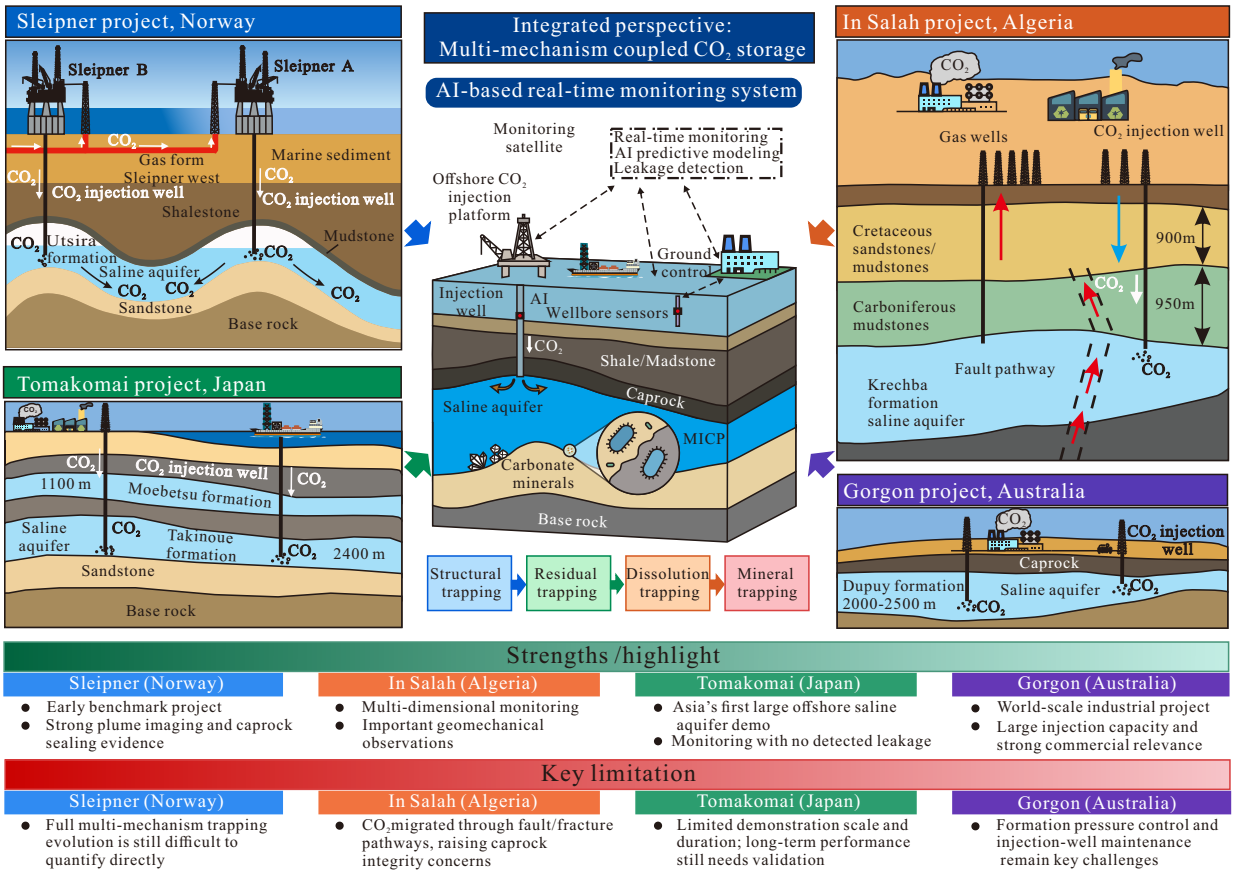


Fig. 3. Typical case analysis of CO_2 storage in a saline aquifer (modified from Sengul (2006), Flett et al. (2009), Mathieson et al. (2010) and Tanaka et al. (2017)).

caprock sealing of this formation provide a natural barrier for CO_2 containment (Furre et al., 2017). Sleipner is also notable for its comprehensive monitoring system. Multiple time-lapse seismic surveys conducted between 1994 and 2010 clearly tracked the CO_2 plume with no evidence of leakage, providing positive empirical validation of the critical role of caprock sealing integrity (Izadian, 2024).

7.2 In Salah project, Algeria

The In Salah project, located in the Sahara Desert region of Algeria, was developed as a joint venture between BP, Sonatrach, and Statoil. The captured CO_2 was injected through three horizontal wells into the Carboniferous sandstone Krechba Formation at a depth of 1,880 m. This formation had a thickness of 20 m, a porosity of 17%, and an overlying caprock up to 950 m thick. It mainly consists of a saline aquifer (Ringrose et al., 2013). The project used a multi-dimensional monitoring system, including time-lapse seismic surveys, microseismic monitoring, and satellite InSAR, to track CO_2 plume migration and formation response in real time. Monitoring recorded 20 mm of surface uplift and thousands of injection-induced microseismic events (Trémosa et al., 2014). Monitoring in 2011 showed that CO_2 did not migrate as expected but spread through fault zones, raising concerns about caprock sealing integrity. The injection was suspended while monitoring continued (Trémosa et al., 2014). This empirical evidence also corroborates, from a negative perspective, the critical role of caprock sealing integrity.

7.3 Tomakomai saline aquifer storage project, Japan

The Tomakomai project is Asia's first large-scale offshore saline aquifer carbon storage demonstration project. Initiated by Japan's Ministry of Economy, Trade and Industry in 2012, the project was constructed in Tomakomai City, Hokkaido. The captured CO_2 was treated using an activated amine process, transported through an approximately 0.2 km pipeline to a nearby compression station, and injected after the pressurization into the Moebetsu Formation at 1,100 m and the Takinoue Formation at 2,400 m below the nearby seabed through two directional wells (Tanaka et al., 2017). The injection began in 2016. By November 2019, the project had reached its planned demonstration target, with a cumulative injection of 3.0×10^5 tons of CO_2, after which the injection was suspended as scheduled. A comprehensive monitoring system was deployed throughout the operation, including time-lapse two-dimensional and three-dimensional seismic surveys, reservoir temperature and pressure measurements, microseismic and natural earthquake observations, and environmental surveys. No CO_2 leakage was detected in the monitoring data (Tanase and Tanaka, 2021).

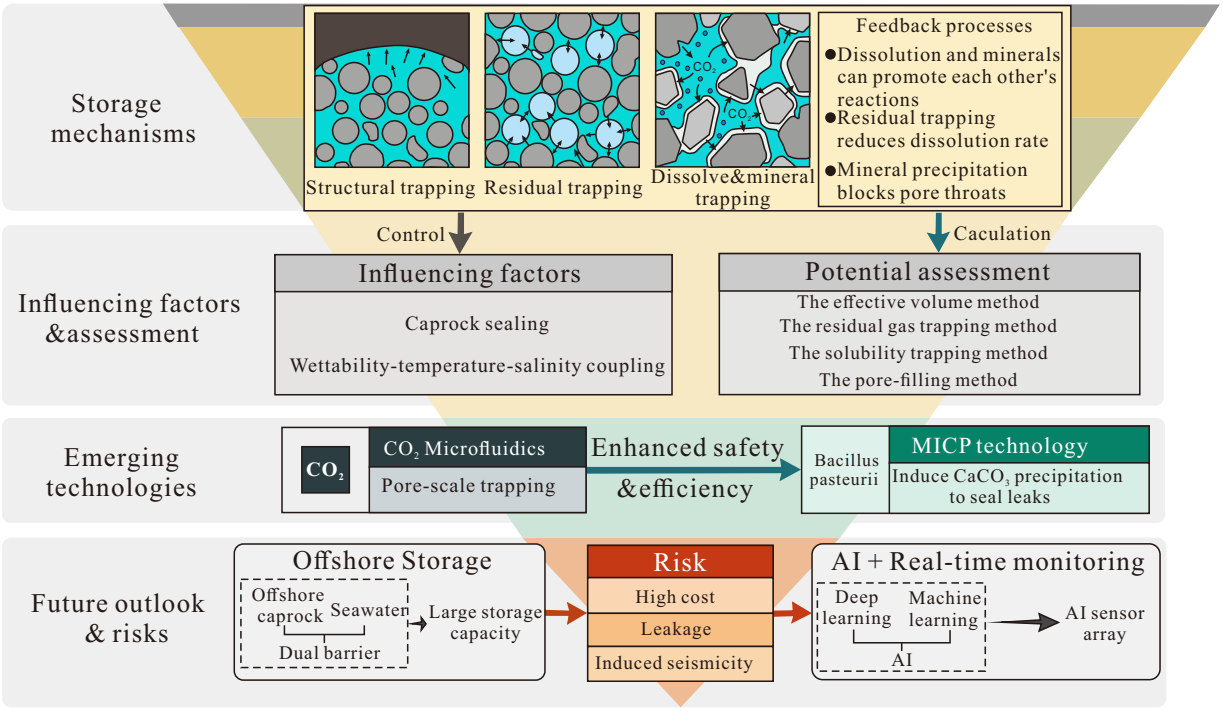


Fig. 4. Research framework for CO_2 geological storage in saline aquifers.

7.4 Gorgon project, Australia

The Gorgon CCS project in Australia is one of the world's largest geological CO_2 storage projects in saline aquifers. Operated by Chevron, the project is located in the Barrow Island Nature Reserve, Western Australia. Associated CO_2 separated during natural gas extraction is injected into the deep Dupuy Formation saline aquifer, approximately 2 km below the island, at depths of 2,000-2,500 m. The target interval had a total thickness of 200-500 m (Marshall, 2022). The injection officially began in August 2019. The project was designed with an annual storage capacity of approximately 4 million tons. As of July 2025, the cumulative injection exceeded 11 million tons. However, formation pressure control, injection-well maintenance, and related operational issues remain major challenges that require long-term, real-time monitoring and refined reservoir management (Mei et al., 2025).

7.5 Insights from comparisons of representative projects

The four representative projects offer complementary field-scale evidence of the performance and limitations of CO_2 storage in saline aquifers. At Sleipner, field experience demonstrates the effectiveness of time-lapse seismic imaging and caprock containment, although the relative contributions of individual trapping mechanisms remain difficult to quantify directly (Izadian, 2024). In Salah illustrates how pressure evolution, geomechanical deformation, and fault-controlled migration affect storage, demonstrating that favorable caprock thickness alone cannot guarantee security (Trémosa et al., 2014). Tomakomai demonstrates the feasibility of offshore saline aquifer storage with integrated geophysical, pressure, seismic, and environmental monitoring, although its relatively limited injection scale and duration constrain assessments of long-term trapping evolution (Tanase and Tanaka, 2021). In comparison, Gorgon illustrates industrial-scale deployment and the practical constraints associated with formation-pressure management, injectivity, and well maintenance (Mei et al., 2025).

Collectively, these cases indicate that storage performance depends on interactions among geological, hydrodynamic, geomechanical, and operational processes, rather than on any single trapping mechanism or monitoring indicator. Therefore, reliable assessments should combine plume imaging with pressure and geomechanical monitoring, well-integrity evaluation, and long-term geochemical characterization. Future storage in saline aquifers should also link the analysis of multiple trapping mechanisms with AI-assisted real-time monitoring and predictive reservoir management. This integration should support early warning, adaptive injection control, and long-term storage security (Fig. 3).

8. Discussion

This section comprehensively reviews the mechanisms, risks, and future directions of CO_2 storage in deep saline aquifers and summarizes the framework diagram of CO_2 geological storage in saline aquifers (Fig. 4). It systematically elucidates the dual functionality of MICP in both leakage pathway sealing and CO_2 mineralization enhancement, the cost and leakage challenges facing global deployment, and the strategic advantages of offshore storage. Critically, this section constructs a multi-technology integrated intelligent synergistic system that takes offshore reservoirs as the application scenario, MICP biomineralization as the core enhancement

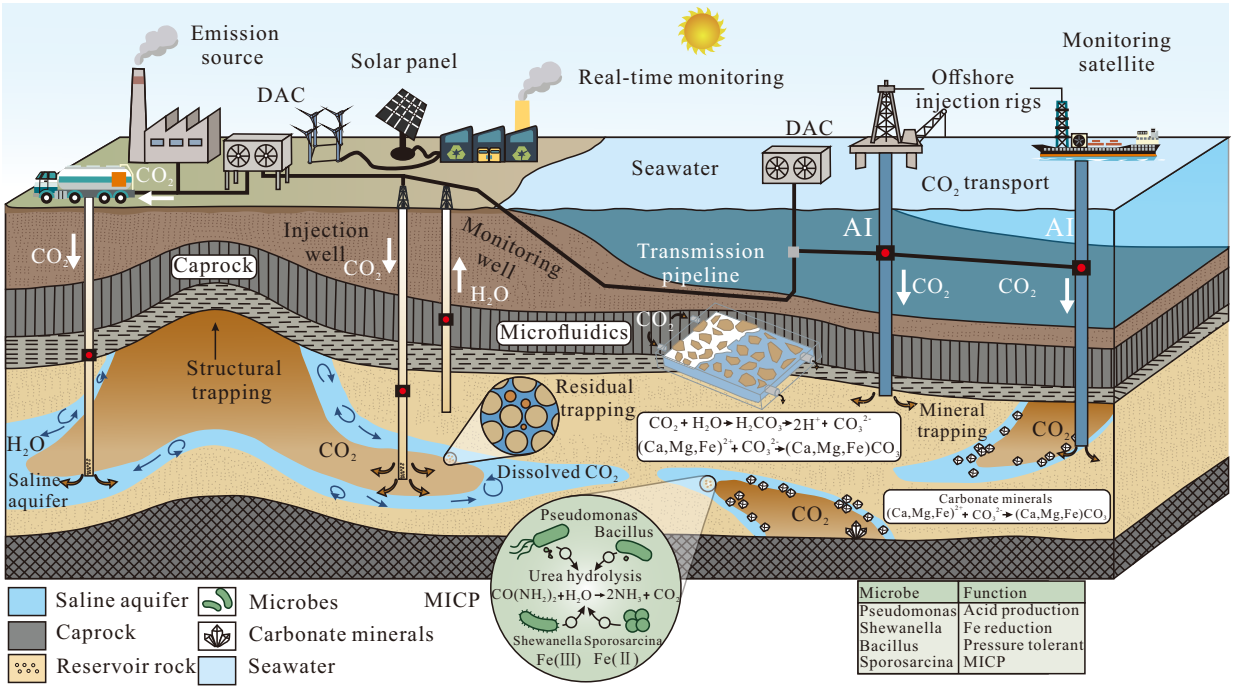


Fig. 5. Conceptual model for future CO_2 storage in saline aquifers.

mechanism, microfluidics technology as the pore-scale characterization tool, and AI as the real-time monitoring instrument (Fig. 5), responding to the field's evolution from static, single-factor assessments toward dynamic, multi-mechanism coupled, and bio-intelligent active regulation.

8.1 Research on the mechanism of CO_2-rock-microbe interactions in deep saline aquifers

Global research on CO_2-rock-microbe interactions in deep saline aquifers remains limited, and most current conclusions are based on laboratory experiments. Available experimental evidence indicates that microorganisms can influence rock weathering and CO_2-water-rock reactions through their metabolic activities and products (Tang et al., 2022; Nixon et al., 2025). Field storage environments are more complex than laboratory systems (Snæbjörnsdóttir et al., 2020). The application of microorganisms for CO_2 capture and conversion in saline aquifers may become an important route for improving storage efficiency and supporting large-scale saline aquifer storage (Hu et al., 2021). Among them, MICP technology holds broad development prospects.

In CO_2 geological storage, MICP has two main applications. The first is leakage pathway sealing. Bacterial and cementation solutions can be injected into fractures or high-permeability zones, where calcium carbonate precipitates are formed *in-situ*. These precipitates seal micropores, lower rock permeability, strengthen caprock sealing, and reduce the risk of CO_2 escape (Xiong et al., 2025a, 2025b). The second is CO_2 mineralization enhancement. Some microorganisms secrete carbonic anhydrase and related substances that catalyze CO_2 hydration, accelerate its conversion to CO_3^{2-}, and promote its reaction with Ca^{2+} and Mg^{2+} to generate stable carbonate minerals, thereby enabling permanent CO_2 storage (Wilcox et al., 2025).

Based on the dual-action mechanism of MICP in CO_2 storage in saline aquifers discussed above, future research needs to further address the key scientific and engineering challenges associated with the transition of this technology from laboratory to field applications. First, the deep saline aquifer environment is characterized by high temperature, high pressure, high salinity, and complex geochemical conditions. These extreme factors may significantly affect microbial activity, growth rates, and metabolic products, thereby constraining the efficiency and controllability of the MICP process (Snæbjörnsdóttir et al., 2020). Second, the kinetic process of MICP is regulated by the coupled effects of multiple factors, including bacterial concentration, cementation solution composition, injection rate, pore structure, and fluid flow regime. How to achieve uniform and predictable mineralization distribution in heterogeneous reservoirs remains a critical technical bottleneck that urgently needs to be overcome. Furthermore, with respect to long-term storage security, the stability of calcium carbonate precipitates is subject to variations in formation fluid pH and continued CO_2 dissolution, which may induce redissolution or recrystallization, thereby compromising the sealing effectiveness or permanence of mineral trapping (Lu et al., 2024; Wilcox et al., 2025). Therefore, future research should be devoted to developing pressure-tolerant and halotolerant microbial strains or enzyme preparations adapted to the extreme conditions of deep saline aquifers, constructing multi-field coupled numerical models to predict the spatiotemporal evolution of the MICP process, and integrating emerging technologies to enhance sealing performance. For example, Kludze et al. (2022) proposed coupling MICP with bipolar

membrane electrodialysis for CO_2 capture and conversion in oceans or saline aquifers. bipolar membrane electrodialysis enables precise pH control, where acidic conditions promote CO_2 release and enrichment, while alkaline conditions induce carbonate mineral precipitation and support efficient CO_2 mineral sequestration.

8.2 Risks and challenges

The global deployment of CO_2 geological storage in saline aquifers is mainly constrained by costs and long-term safety. Storage costs cover three stages: Capture, transportation, and storage. Long-term safety remains a central challenge because it directly affects the acceptance and implementation of saline aquifer storage. Major safety failures include CO_2 leakage, surface uplift, and induced seismicity.

High costs have become a key barrier to the large-scale deployment of saline aquifer CO_2 storage. First, many saline aquifer sites lack preliminary geological exploration data, which increases the need for geophysical surveys and engineering investments (Zoback and Gorelick, 2012; Ringrose et al., 2021). Second, monitoring should continue throughout the entire storage life cycle, from injection to hundreds of years after site closure (Akpolat and Bakırtaş, 2024; Cao et al., 2024; Rui et al., 2025). For instance, the Sleipner project in Norway incurred substantial costs for conventional seismic monitoring and repeated time-lapse seismic surveys (Ling et al., 2024; Rui et al., 2025). Third, drilling is another major cost component. During site construction, reservoir heterogeneity may require a higher drilling density, whereas anti-corrosion pipe materials further increase expenditure (Anders et al., 2024; Wang et al., 2025b; Zhang et al., 2025a). These costs increase the initial investment threshold, reduce the cost recovery potential, and restrict large-scale development of CO_2 geological storage in saline aquifers.

CO_2 leakage is a focal point of storage safety research. Three main leakage mechanisms have been identified. First, CO_2 injection can increase fluid pressure in saline aquifers beyond the capillary pressure of the caprock, resulting in caprock breach, loss of sealing capacity, and leakage (Verdon et al., 2013; Hu et al., 2022). Second, pressure buildup can alter the stress field, reactivate faults, generate caprock fractures, reduce storage stability, and trigger leakage (Alcalde et al., 2018; Cesca et al., 2021). Third, excessive injection pressure and long-term CO_2 corrosion may cause wellbore sealing failure and leakage (Cesca et al., 2021; Vilarrasa et al., 2022).

8.3 Future directions

CO_2 geological storage in saline aquifers remains below the deployment rate and storage scale required for global warming mitigation. Projects such as Sleipner and Snøhvit have provided long-term operational experience, whereas field validation of large-scale clustered offshore storage remains limited. Therefore, further development of saline aquifer-scale CCUS technologies is crucial for global CO_2 emission reduction.

Offshore storage should be developed as a priority direction. Compared with onshore storage, it can reduce induced seismicity and the damage associated with fluids generated or displaced from drinking aquifers after CO_2 injection (Rahman et al., 2017; Mi, 2023; Lin et al., 2024). Moreover, offshore CO_2 storage sites are distant from human settlements, surface water, and groundwater resources (Zhang et al., 2023). Beyond geological caprock sealing, seawater pressure and barrier effects further reduce systemic risk (Miller and Orton, 2021; Yang et al., 2022; Alhammad et al., 2023). Therefore, offshore storage has become an important trend in future CCUS development.

Future offshore CO_2 storage can be combined with MICP and AI-based monitoring. Under suitable conditions, MICP induces carbonate mineral precipitation, enhances CO_2 mineralization storage, prevents water pollution, and reduces the impact on subsurface ecosystems. Furthermore, microfluidics technology was employed to distinguish the significant differences between MICP and chemically induced carbonate precipitation in terms of crystal induction time, lateral extension width, and vertical distribution (Wilcox et al., 2025). This approach provides a pore-scale visualization platform for elucidating the mineralization mechanism of MICP, thereby overcoming the fundamental limitation of macroscopic experiments in capturing microscopic heterogeneity (Xiao et al., 2024). Meanwhile, AI-based monitoring and machine learning (ML) can support real-time performance monitoring of the storage process, thereby reducing CO_2 leakage and subsurface risks (Alotaibi and Nassif, 2024; Carrascal-Hernández et al., 2025). Unlike traditional monitoring techniques that rely heavily on manual inspection and numerical simulations, AI and ML can improve monitoring efficiency, accelerate risk responses, and reduce costs (Lowe et al., 2022; Wang et al., 2024). Further research is required to assess the long-term stability, carbon sequestration efficiency, and subterranean ecosystem impacts of this coupled system under actual geological conditions. Therefore, based on the visualization platform provided by microfluidics, an integrated offshore storage system combining MICP-enhanced storage and AI-enabled real-time monitoring is expected to improve both storage efficiency and operational safety (Fig. 5). This pathway may provide a practical and sustainable approach to CO_2 storage and carbon neutrality.

8.4 Comparison with previous studies

CO_2 storage in saline aquifers has been extensively studied. Early studies focused primarily on assessing geological CO_2 storage potential in saline aquifers (Song et al., 2026), mainly using the volumetric method (Goodman et al., 2011) and the mechanistic approach (Bachu et al., 2007). Subsequent studies examined how wettability, temperature, and salinity affect mineralization and storage efficiency after CO_2 injection into saline aquifers (Khoramian et al., 2026). They also reviewed the progress, challenges, and future prospects of mineral trapping (Khan et al., 2026). Researchers have also investigated the factors influencing CO_2 kinetics and geochemical reactions (Tan et al., 2026) and explored the potential development of MICP (Wei et al., 2025), microfluidics (Zhong et al., 2026),

and AI technologies (Yang et al., 2026) for CO_2 storage in saline aquifers.

The present study advances beyond these investigations in several ways. First, previous research established two principal approaches for estimating CO_2 storage capacity in saline aquifers: The volumetric method (Goodman et al., 2011) and the mechanistic method (Bachu et al., 2007). Building on this foundation, the present study explicitly incorporates synergistic interactions among multiple trapping mechanisms across temporal scales into the capacity estimation framework. Second, previous studies on storage conditions have predominantly examined individual controlling factors in isolation (Khoramian et al., 2026). The present study instead emphasizes the coupled effects by analyzing the synergistic interactions among wettability, salinity, and temperature within an integrated framework. Some studies have also identified feasible pathways through which MICP accelerates mineralization by promoting carbonate precipitation (Rajasekar et al., 2021; Wei et al., 2025). Other studies have used microfluidics to visualize pore-scale CO_2 migration and mineralization crystallization (Zhong et al., 2026) and explored AI applications in site screening, dynamic prediction, and real-time monitoring (Aminaho et al., 2026; Yang et al., 2026). In contrast, the present study proactively develops a synergistic saline aquifer system by combining offshore storage, MICP, and AI monitoring. This system integrates accelerated biomineralization, pore-scale visualization, and intelligent real-time monitoring. Over the past two decades, research has shifted from single-mechanism static assessments to multi-mechanism coupled dynamic simulations and from passive geological storage to bio-intelligent active regulation. The synergistic system proposed in this study directly responds to this trend (Fig. 5).

Moving beyond the limitations of previous single-factor analyses, this study is the first to incorporate caprock sealing integrity and the coupled wettability-salinity-temperature effects into a unified analytical framework, thereby systematically revealing the evolutionary patterns of storage efficiency under multi-factor synergy. Furthermore, MICP technology is examined, and a prospective synergistic system combining offshore storage, MICP, and AI monitoring is proposed for saline aquifers. This framework provides a potential pathway for large-scale intelligent carbon storage.

9. Conclusions

The successful operation of international projects, including Sleipner in Norway and Gorgon in Australia, demonstrates why deep saline aquifers are widely regarded as the most promising geological media for large-scale, long-term CO_2 storage. Structural, residual, solubility, and mineral trapping evolve through coupled processes that govern storage in these aquifers. Caprock sealing integrity and interactions among wettability, salinity, and temperature critically control storage efficiency. Therefore, this study develops an integrated analytical framework for geological CO_2 storage in saline aquifers that connects mechanism characterization, condition evaluation, capacity assessment, case analysis, and risk identification.

Despite this potential, practical barriers remain, including high operational costs, uncertainties regarding long-term safety, and risks of induced seismicity. To address these challenges, offshore storage should be prioritized to exploit its inherent safety and spatial advantages. Fundamental research on CO_2-rock-microorganism interactions should be strengthened, with particular attention to the microscopic mechanisms through which MICP improves storage efficiency. AI and ML should be integrated into intelligent real-time monitoring and early warning systems to improve controllability and safety throughout the storage lifecycle.

This study makes two core innovative contributions. First, it clarifies the multiple microscopic mechanisms through which MICP enhances carbon storage in saline aquifers and provides a theoretical basis for bio-enhanced CO_2 sequestration. Second, it establishes a framework that integrates offshore storage, MICP, and AI monitoring. By combining spatial optimization, bioaugmentation, and intelligent management, this framework offers a systematic pathway toward large-scale, intelligent carbon storage in saline aquifers.

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Supplementary file

https://doi.org/10.46690/ager.2026.10.03

Conflicts of interest

The authors declare no competing interest.

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