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Review article

Scientific Mechanisms, Technical System, and Engineering Pathways of Synergistic Geological Sequestration of Mine Water and Carbon Dioxide

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Abstract:
Against the backdrop of global climate change mitigation and China's deepening "Dual Carbon" strategy, geological carbon dioxide (CO_2) sequestration has become a key technology for large-scale emission reduction. However, its widespread application is hindered by challenges such as poor economic viability and leakage risks. Meanwhile, the safe and efficient disposal of the massive amounts of mine water generated in China's major coal-producing regions has become an urgent environmental issue. To simultaneously address the dual challenges of "carbon sequestration" and "water management," this paper innovatively proposes a new technology: Mine Water-CO_2 Synergistic Sequestration (MW-CSS). This approach aims to break through traditional single-disposal models by constructing a synergistic system that uses water as a carrier and underground pores as reactors. It transforms mine water from a disposal target into an active medium that drives CO_2 mineralization, thereby promoting CO_2 dissolution, enhancing the stability of the dissolved phase during migration, and providing the necessary ions and reaction conditions for mineralization fixation. This paper systematically elaborates on the synergistic mechanisms and comprehensive advantages of MW-CSS, and proposes a framework covering "efficient mixing, enhanced injection, engineering equipment, monitoring and early warning, and comprehensive evaluation," along with three core process pathways. The study aims to provide key scientific and technological support for the synergistic governance of carbon reduction, pollution control, ecological expansion, and economic growth in China's mining areas.

1 Introduction

Against the global backdrop of climate change mitigation, Carbon Capture, Utilization and Storage (CCUS) has become an indispensable strategic technology for achieving large-scale low-carbon utilization of fossil fuels and safeguarding national energy security. According to statistics from the International Energy Agency (IEA), the global annual CO_2 capture capacity of CCUS projects exceeded 5×10^6 tons CO_2 equivalent by early 2025. Based on current project pipelines, global annual capture and potential storage capacities are projected to surge to approximately 4.3×10^8 million tons and 6.7×10^8 tons, respectively, by 2030, marking the industry's transition from small-scale demonstrations to large-scale deployment (IEA, 2024).

As the core terminal component of the Carbon Capture, Utilization and Storage (CCUS) technology system, CO_2 Geological Storage (CGS) achieves permanent CO_2 sequestration through formation physical trapping, dissolution, and mineral carbonation. Since Koide et al. (1992) proposed the concept of deep formation storage in the 1990s, the Sleipner saline aquifer project in the North Sea, completed in 1996 as the first

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large-scale industrial demonstration, has validated the long-term safety of geological storage with over two decades of continuous monitoring data (Furre et al., 2017). At the current stage, the global research focus has shifted from single physical sequestration to collaborative chemical mineralization sequestration. The CarbFix project in Iceland achieved over 95% mineralization and solidification of CO_2 within two years by co-injecting CO_2 and fresh water into basalt formations (Matter et al., 2016); however, this model relies on high-permeability basalt and low-mineralized makeup water, making it difficult to be directly adapted to the geological conditions of coalfields in China.

Domestic CCUS storage projects have also developed rapidly in tandem. The Shenhua Ordos continental saline aquifer demonstration project has verified the feasibility of storage in complex sedimentary formations (Xie et al., 2016). The successive launch of the Qilu Petrochemical megaton-scale storage project and the Huaneng Zhengning project marks that China's CCUS technology is transitioning from industrial demonstration to commercial clustering. According to assessments, China's theoretical geological storage capacity can reach the trillion-ton level, demonstrating enormous potential for large-scale application (Sang et al., 2023). However, traditional CGS technology still faces a series of common challenges. First, the slow mineralization reaction restricts long-term safety. The carbonation rate of typical minerals takes hundreds of years or more, which prolongs the time required for storage sites to reach a long-term stable state and increases the potential long-term risk of CO_2 leakage due to caprock failure or fault activation. Second, the monitoring, prediction, and verification technologies for the underground migration and distribution of CO_2 plumes still need to be developed, which affects regulatory approval and public acceptance. Existing geophysical technologies mostly have a spatial resolution of the order of ten meters for CO_2 plumes, making it difficult to achieve high-resolution, real-time, and cost-effective three-dimensional plume characterization. There are uncertainties in the identification of CO_2 migration and leakage pathways as well as the quantitative assessment of long-term safety, which further affects project regulatory approval, risk quantification, and public acceptance. Third, the high cost of the entire process weakens economic viability. Storage costs, combined with expenses for transportation, site characterization, injection well construction, long-term monitoring, and other aspects, are exorbitant, while there are few additional benefits during the storage process. This makes projects lack commercial competitiveness in most regions where there is no strong carbon pricing mechanism or sufficient financial subsidies.

Meanwhile, mining activities in western China's coal bases are accompanied by the generation of a large volume of high-salinity mine water. Traditional disposal methods such as surface evaporation and membrane desalination require extensive land occupation, involve high energy consumption, and incur persistently high operation and maintenance costs. Geological Deep Well Injection and Storage (GDWIS) provides a new solution for the safe disposal of such refractory wastewater (Du et al., 2026). The geological storage team of the Exploration and Research Institute of China National Administration of Coal Geology has carried out a series of pioneering works in the Ordos Basin. The scientific research and demonstration project has achieved a stable injection capacity of 200 cubic meters per hour for a single well, and the treatment cost can be reduced by approximately 80% compared with the traditional evaporation pond technology.

Based on the complementary characteristics of the two technologies of traditional CGS and deep mine water storage, this paper proposes the "Mine Water-CO_2 Synergistic Sequestration" (MW-CSS) technology system. This system innovatively utilizes the primary pore system of suitable deep sandstone formations for storage, transforming mine water from a passively disposed object into a reaction solvent and ion source that actively drives CO_2 fixation. It constructs a "physical dissolution-chemical mineralization" synergistic sequestration system, and develops three types of engineering processes adapted to low-permeability coalfield reservoirs, namely surface pre-dissolution, modified water-alternating-gas injection, and simultaneous wellbore injection. Additionally, it establishes low-cost dedicated monitoring methods based on the high electrical conductivity characteristics of mine water. This study systematically clarifies the synergistic reaction mechanism, multi-field coupling evolution law, complete set of engineering technologies, and regional site selection evaluation methods of MW-CSS, providing an integrated low-carbon engineering solution for simultaneously achieving carbon sequestration and resource-based disposal of mine wastewater in coal-producing areas.

2 Research progress of deep geological storage of carbon dioxide and mine water

2.1 Research status of MW-CSS

CO_2 and fluid co-injection technology originally evolved from the water-alternating-gas (WAG) flooding process for oil and gas reservoirs. Since the 1950s, this technology has been proven in multiple oilfields worldwide to achieve dual benefits of enhanced oil recovery and carbon sequestration by regulating fluid mobility and stabilizing the displacement front. Juanes et al. (2006) found that alternately injected water slugs can effectively break up continuous CO_2 plumes and promote their diffusion and distribution, thereby enhancing capillary and dissolution trapping mechanisms. Oak et al. revealed the strong path dependence of relative permeability relationships in the CO_2-brine-rock system through precise core experiments, providing key parameters for numerical simulation (Koide et al., 1992).

In engineering practice, simulation studies by Eke et al. (2011) showed that pre-dissolving CO_2 in brine before injection can significantly mitigate the risk of buoyancy-driven leakage and significantly shorten the underground immobilization time. This technology was successfully engineered in Iceland's CarbFix project (Matter et al., 2016), where CO_2 was mixed with water at a ratio of approximately 1:28.5 and co-injected into basalt reservoirs, accelerating mineral carbonation in the dissolved phase and proving the feasibility of the technical route. Experiments by Rathnaweera et al. (2016) quantitatively

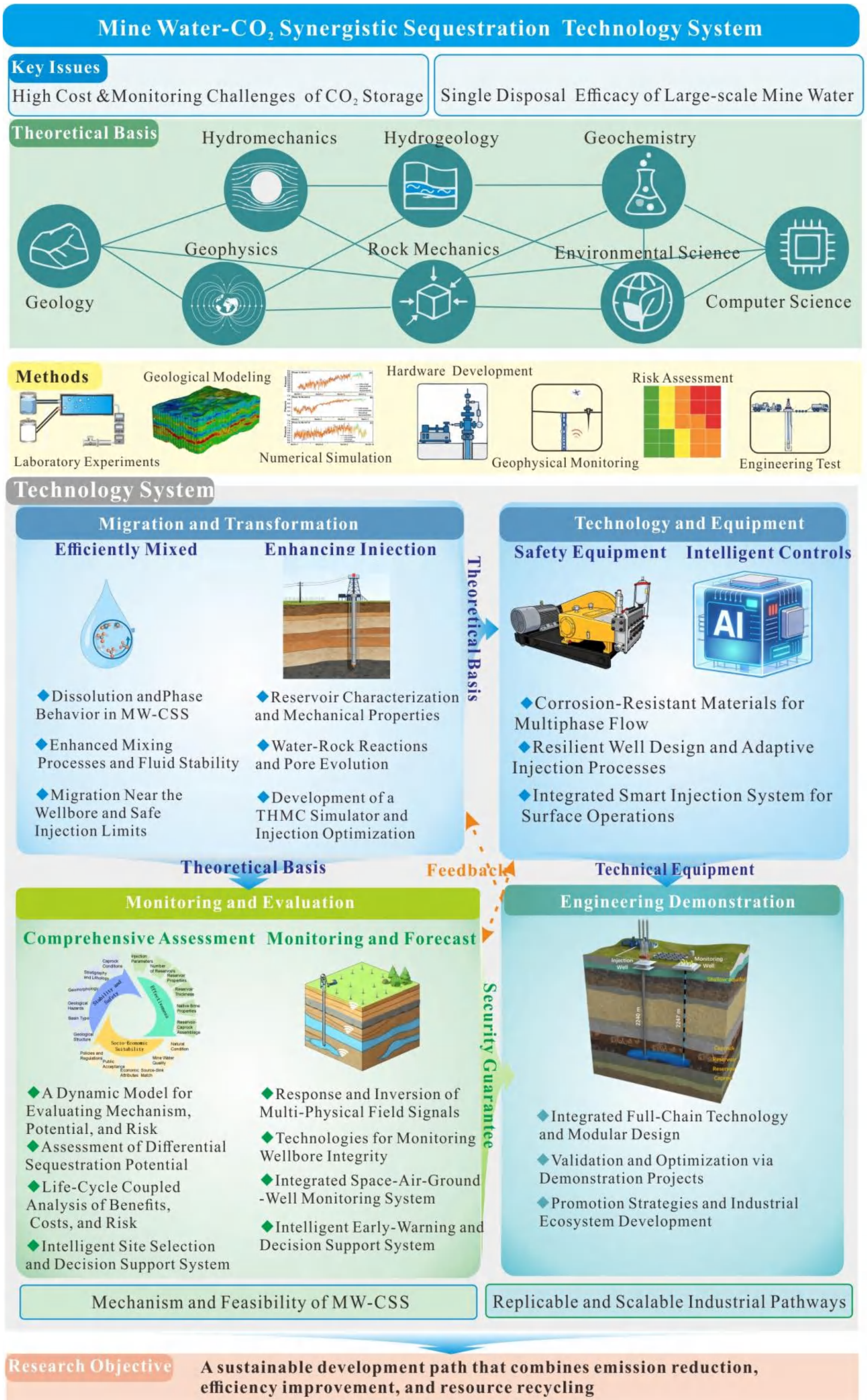

Fig. 1 Technology system of MW-CSS

revealed the enhancement effect of co-injection, indicating that CO_2-brine co-injection can significantly improve the dissolution trapping rate and storage safety compared with traditional single injection.

However, current research still has obvious limitations: the CarbFix project relies on specific high-permeability basalt reservoirs and huge water consumption; domestic tests are still in the initial stage. For the low-permeability and heterogeneous sandstone reservoirs prevalent in China's coal mining areas, and the synergistic storage system where mine water with complex components replaces freshwater or simple brine, systematic solutions and process flows have not yet been formed regarding long-term injectability, mineral reaction paths, storage stability, and full-process economy.

2.2 Technical advantages of CO_2-water synergistic sequestration

MW-CSS achieves systematic improvements in sequestration efficiency, safety, and economy through chemical reaction-driven mechanisms and systems engineering integration (Tab.1). At present, no systematic research on this technology has been conducted globally. The international academic community has carried out a series of fundamental studies on the stability and efficiency of CO_2-water co-injection. Water-rock chemical reactions drive the dissolution and precipitation evolution of reservoir minerals, and geochemical simulation is the core approach to characterize this process. However, key parameters such as equilibrium constants, reaction rates, and mineral specific surface area exhibit significant discreteness in values, which directly increases the uncertainty of numerical simulation results. The relevant parameter system can support numerical simulation and risk assessment of multiple types of saline aquifer sequestration (Liu et al., 2020). The large-scale offshore saline CCS demonstration project Gorgon in Australia has established a standardized full-process environmental risk assessment framework. By hierarchically identifying risk sources and sensitive ecological receptors, and classifying risk levels in combination with the consequence-likelihood matrix with supporting control measures, its complete evaluation framework can provide a mature reference paradigm for the environmental safety assessment of continental saline aquifer sequestration projects in China (Li et al., 2019). Long-term operation data from multiple commercial saline aquifer sequestration projects worldwide, including Sleipner and Weyburn, as well as the Ordos project in China, have confirmed the feasibility of large-scale carbon sequestration in saline aquifers. Sequestration involves three sequential dominant mechanisms: physical trapping, dissolution trapping, and mineral solidification. Differences in lithology and hydrochemistry between continental and marine sedimentary reservoirs can significantly alter the long-term sequestration and transformation patterns of CO_2 (Li et al., 2012).

At the sequestration mechanism level, synergistic sequestration shows significant chemical and kinetic complementarity. Different from traditional saline aquifer sequestration which relies on limited ions in formation water for slow mineralization and the physical mobility control and sweep efficiency of WAG, the core of MW-CSS lies in utilizing the carbonate mineralization precursor ions such as Ca^{2+} and Mg^{2+} rich in mine water itself, as well as Fe^{2+} with reaction potential under reducing conditions. Theoretically, it actively creates a chemical environment conducive to CO_2 dissolution and carbonate precipitation, improving the rate and degree of sequestration and solidification. In terms of stability and safety guarantee, MW-CSS pre-dissolves CO_2 or co-injects it with mine water to form a high-density single-phase liquid fluid, which can significantly reduce the risk of caprock leakage caused by CO_2 phase floating from the source (Paluszny et al., 2020). This process mainly utilizes and modifies the existing micro-pore-micro-fracture system of the reservoir, and gradually seals and reinforces the pore throats through mineralization reactions, rather than creating macro-fractures through fracturing. Thus, while improving the sequestration capacity, it maintains the natural mechanical integrity of the reservoir and caprock.

At the economic and strategic level, MW-CSS is expected to integrate and offset CO_2 sequestration costs and mine water disposal costs, and can share infrastructure such as wellbores and monitoring networks, thereby significantly diluting fixed asset investment and reducing the marginal cost of per-ton carbon sequestration (Eke et al., 2011). This "treating waste with waste and achieving synergistic efficiency" model provides an economically sustainable comprehensive solution for mining areas to simultaneously address emission reduction and environmental protection challenges.

2.3 Key scientific and technological challenges and connotation of synergistic sequestration system

Currently, MW-CSS is still in the stage of theoretical conception and small-scale simulation tests. There are four types of interdisciplinary core bottlenecks from laboratory mechanism research to large-scale engineering implementation:

(1) The boundary of synergistic efficiency enhancement is not yet clear. There is a lack of quantitative demonstration on whether the coupled system of mine water and CO_2 can stably generate net benefits exceeding single sequestration; the gas-liquid two-phase fusion limit and ion competitive reaction thresholds under different temperature, pressure and salinity conditions have not been clarified.

(2) The dynamic behavior and evolution law of multiphase multi-component fluids are unclear. The dissolution-desorption mechanism of CO_2 under deep conditions and its impact on leakage risk are not well understood; the strong thermal-hydro-mechanical-chemical (THMC) multi-field coupling mechanism among mine water, CO_2 and low-permeability heterogeneous reservoir rocks, especially competitive precipitation and microscopic migration laws, is still difficult to quantitatively predict.

(3) There are gaps in the adaptive engineering technology system. Corrosion and scaling control of wellbores and injection equipment, efficiency-enhanced injection processes for low-permeability reservoirs, as well as specific monitoring and early warning technologies for synergistic systems, all urgently need to be developed.

(4) The full-chain technical support system is missing. From technical standards, policies and regulations to clear business

Tab. 1 Comparison of three types of sequestration technologies from the perspectives of sequestration mechanism, engineering attributes and system objectives

Item	GDWIS	CGS	MW-CSS
Research Start Time	After 2019	1990s	2025
Original Research Purpose	Reduction of excessive mine water and terminal disposal of high-salinity water	Oil and gas displacement, carbon emission reduction	Terminal disposal of gas/liquid fluids
Target Storage Area	Deep porous sandstone formations	Oil and gas reservoirs, saline aquifers, unmineable coal seams, special spaces	Deep porous sandstone formations
Storage Mechanism	Pore confinement in deep sandstone	Pore confinement, structural trapping, dissolution, mineralization	Pore confinement, dissolution, mineralization
Storage Formation	Deep formations far from usable aquifers	Oil and gas reservoirs, saline aquifers, unmineable coal seams, special spaces, etc.	Deep formations far from usable aquifers
Recommended Depth	> 2000 m	> 1000 m	> 2000 m
Typical Research Projects	Deep geological storage technology research and demonstration project of the geological storage team of the Exploration and Research Institute of China National Administration of Coal Geology	Sleipner, Weyburn, Illinois Basin, In Salah	No demonstration projects yet
Energy Consumption	Low	High energy consumption for CO_2 temperature control	Relatively low
Maximum Storage Capacity of Single Project	10 million m^3/a	1.5 million t/a (Longship project as example)	Expected: 1 million m^3 of mine water, 50,000 t of CO_2
Research Maturity	Relatively complete technical system established	Relatively mature research abroad	Still in the exploration stage
Primary Trapping Mechanism	Physical storage	Dominated by physical storage, supplemented by mineralization storage	Synergistic enhancement of physical-chemical interactions
Source-Sink Matching	Good	Requires specific planning, generally poor matching	Regionally variable(generally suitable in Ordos-type basins)
Policy Support Level	Uncertain	Strong support	Can refer to CO_2-related policy support
Storage Cost	Low	High	Low
Economic Analysis	Low construction cost, low operation cost	High construction cost, high operation cost	Low construction cost, low operation cost
Market Prospect	Good	Great future prospect	Good
Market Demand	Mainly concentrated in areas with large mine water outflow in the Yellow River Basin	Partial demand under the “Dual Carbon” target constraints, expected large demand in the future	Large demand in large-scale energy bases in the future under “Dual Carbon” and environmental protection constraints
Environmental Impact Risk	Low risk	Low risk	Low risk
Monitoring Technology	Relatively complete monitoring technology, good monitoring effect, controllable cost	Has leakage monitoring means but no fluid migration monitoring means, high cost	Monitored through the dual medium properties of water and CO_2

models and multi-party cooperation mechanisms, all restrict its engineering implementation and promotion.

Based on the above systematic review of domestic and international multiphase co-injection theories and engineering practices, the Mine Water-CO_2 Synergistic Sequestration (MW-CSS) technology system shows systematic transformative potential in breaking through bottlenecks such as the high cost and limited monitoring of traditional sequestration, as well as the single function of deep mine water disposal. This system redefines mine water rich in multiple ions from a traditional “waste stream for disposal” to an underground sequestration carrier “with chemical activity and transport function”.

In future development and engineering implementation, guided by the interdisciplinary theories of hydrogeology, engineering geology, groundwater dynamics, fluid mechanics, geochemistry, geophysics, environmental science, materials science, mechanical engineering, computer science, etc., following the overall idea of basic theoretical analysis, technology and equipment research and development, system software development, and on-site engineering tests, and adopting methods such as 3D modeling, laboratory experiments, numerical simulation, geophysical exploration monitoring, software and hardware research and development, and environmental risk assessment, mine water and CO_2 are converted into fluids suitable for underground sequestration through efficient mixing and phase state regulation technologies; the expected dissolution or mineralization reactions underground are guided through multi-field coupling efficiency-enhanced injection technologies; the fluid is safely and gently injected into the micro-pore system of deep sandstones relying on special corrosion-resistant equipment and intelligent injection processes; the integrated monitoring and early warning network and dynamic comprehensive evaluation system continuously evaluate safety and optimize operation strategies. Finally, systematic integration verification and iterative technology upgrading are carried out through full-chain engineering demonstrations. The goal is to form a complete technical chain with "controllable processes, perceivable states, and evaluable efficiency", which is expected to greatly reduce the economic and environmental thresholds for global CCUS deployment, and especially provide a sustainable development path combining emission reduction, efficiency enhancement and resource recycling for regions rich in coal resources and industrial countries facing water treatment challenges.

3 High-efficiency and low-cost enhanced mixing technology of mine water-CO_2

Mine Water-CO_2 Synergistic Sequestration (MW-CSS) shows dual kinetic advantages of dissolution trapping and active mineralization in terms of chemical mechanism, and provides a green path at the engineering level. However, to transform this macro strategy into safe filling at the geological scale, the primary bottleneck lies in how to achieve efficient, low-energy consumption physical and chemical transformation of gaseous CO_2 and mine water rich in multiple ions on the ground or in the near-wellbore area. The hydrodynamic characterization and phase state distribution of the mixed fluid are the keys to determining whether it can be gently injected into deep heterogeneous sandstone, uniformly swept, and blocked from buoyancy floating. Therefore, this chapter focuses on the "High-Efficiency and Low-Cost Enhanced Mixing Technology of Mine Water-CO_2", systematically analyzes the research status of high-efficiency gas-water mixing, the mechanism of multi-phase mass transfer enhancement, and the long-term stable regulation process, laying a process physical foundation for subsequent deep efficient injection and safety monitoring.

3.1 Research status of high-efficiency gas-water mixing

Gas-water mixing is the pre-core process of the entire MW-CSS process. The uniformity and phase stability of the mixed fluid directly determine the injection effect of deep reservoirs. Preparing stable gas-liquid mixed fluids through physical and chemical coupling means can fundamentally inhibit the accumulation of free CO_2 gas phase and avoid formation safety hazards caused by fracturing disturbances; the core research contents of this link include four directions: phase state prediction of gas-water system, mass transfer enhancement process, long-term stable regulation of fluid, and near-wellbore reservoir protection.

Domestic and foreign research in the field of CO_2 enhanced dissolution provides an important foundation for MW-CSS. The solubility law of CO_2 in pure water or simple brine has been relatively clear. Studies have shown that low temperature and high pressure are conducive to dissolution, while salt ions (especially divalent cations) will inhibit solubility through the "salting-out effect", and for every 1 wt% increase in salinity, the solubility of CO_2 decreases by about 1.0%-1.5% (Guo et al., 2018). To break through mass transfer limitations and achieve efficient dissolution and long-term stability of CO_2, the research frontier is focusing on the synergistic enhancement of multiple means such as physics, chemistry, and materials. In terms of physical enhancement, domestic demonstration studies show that downhole generation of submicron CO_2 microbubbles can effectively improve the injection uniformity of low-permeability reservoirs and significantly increase the storage rate (Li et al., 2024). Basic research further reveals that local flow field disturbance around microbubbles is the core mechanism of enhanced mass transfer (Lin et al., 2019). Cutting-edge international research reveals that in nanochannels composed of two-dimensional materials such as graphene oxide, confined water can increase CO_2 solubility by an order of magnitude (Rao et al., 2023). In terms of chemical and material enhancement, foreign studies have successfully increased CO_2 absorption efficiency by 2 times by coating a specific polymer film on the surface of amino acid solution (Yang et al., 2024). The introduction of catalysts and nanomaterials is another important direction. In acid gas capture and absorption processes, the addition of amine activators or composite nanoporous carbon materials can greatly increase the adsorption capacity and dissolution rate of CO_2 (Chai et al., 2025; Baba et al., 2026). For example, carbonic anhydrase (CA) can greatly accelerate the CO_2 hydration reaction rate, and its composite system with amine absorbents shows a significant synergistic effect (Ting et al., 2023).

In addition, despite the significant progress mentioned above, most existing studies are based on systems with relatively single components. For mine water with complex components, its high ionic strength and dynamic chemical reactions pose challenges to traditional solubility models (Du et al., 2025, 2026). At the same time, it may accelerate physical scaling and clogging of nanomaterials, or interfere with the surface activity of microbubbles due to competitive coordination.

3.2 Key technologies of high-efficiency gas-water mixing

(1) Phase state regulation and solubility prediction of mine water-multi-phase CO_2 mixed system

Relying on high-temperature and high-pressure reactors, systematically determine the solubility of CO_2 in a series of typical mine waters, and draw temperature-pressure-solubility/reaction rate phase diagrams with salinity and key ion ratios as key variables. Quantitatively reveal the influence of active ions such as Ca^{2+} and Mg^{2+} as reaction precursors on the thermodynamic equilibrium of mineralization crystallization and precipitation kinetics (Chapoy et al., 2004), as well as the "salting-out" inhibition law of inert ions such as Na^+ and Cl^- on the physical solubility of CO_2.

(2) Adaptive mixing process enhancement and fluid stability regulation

Develop and integrate physical mass transfer enhancement technologies such as temperature and pressure condition control, micro/nano bubble generation, and vortex super-shearing to achieve efficient gas-liquid contact with minimum energy consumption. Screen and develop chemical additives such as green corrosion inhibitors and crystal modifiers to regulate the mineralization reaction rate and product morphology, and avoid pipeline scaling (Pan et al., 2025). At the same time, systematically characterize key physical properties of the mixed fluid such as density, viscosity, and pH, study its corrosion/scaling mechanism on pipeline materials, and form technical specifications to ensure the stability of the fluid from preparation to the wellhead.

(3) Safe injection in near-wellbore area and reservoir protection

Adopt a combination of experimental simulation and numerical simulation to reveal the migration behavior of mine water with different qualities (low-salinity fluid rich in dissolved CO_2 and high-salinity reactive fluid) in the transition zone from the wellbore to the reservoir: for low-salinity fluid rich in dissolved CO_2, early warning of CO_2 gas precipitation risk caused by pressure drop (Yan et al., 2025); for high-salinity reactive fluid, prevent the risk of pore clogging caused by excessive mineral precipitation in the near-wellbore high-temperature environment. At the same time, reveal the interaction between injected fluids and mineral particles and clay minerals in low-permeability sandstone reservoirs, clarify the composite damage mechanism of "velocity sensitivity-salt sensitivity-acid sensitivity" (Ghiasi et al., 2026), and determine the critical injection rate and pressure threshold to ensure the microstructural integrity and long-term injectability of the reservoir.

4 Multi-field coupling reaction between mixed fluid and formation and efficiency-enhanced injection technology

After realizing the efficient and low-cost preparation of mine water-CO_2 co-injection fluid on the surface or at the wellhead through the above-mentioned gas-water mixing and phase state regulation technologies, the core of the process immediately shifts to the safe and efficient injection stage of deep underground reservoirs. When the prepared multiphase or single-phase co-injection fluid crosses the wellbore and enters the deep heterogeneous sandstone reservoir thousands of meters underground, the fluid not only faces a complex temperature field and high-pressure pore environment, but also breaks the original rock-formation water chemical equilibrium. The interweaving of physical transport and multiphase chemical reactions will trigger a complex THMC multi-field coupling response within the reservoir (Du et al., 2026). To achieve uniform migration and efficient in-situ mineralization of mixed fluids in the micro-pore system without damaging the natural integrity of the formation, it is necessary to clarify the dynamic evolution mechanism of the reservoir under deep multi-field coupling. Therefore, this chapter focuses on the "multi-field coupling reaction between mixed fluid and formation and efficiency-enhanced injection technology", and deeply analyzes the research status and technical directions of deep chemical reaction kinetics, dynamic evolution of reservoir physical properties, and intelligent low-damage regulation strategies.

4.1 Research status of multi-field coupling reaction and efficiency-enhanced injection

Injecting mine water mixed fluid containing dissolved/co-injected CO_2 into deep formations will change the original geochemical equilibrium and trigger THMC multi-field coupling. Therefore, under the engineering constraints that large-scale hydraulic fracturing is prohibited and only low-damage reservoir regulation is allowed, how to achieve effective injection and efficient mineralization of mixed fluids in the micro-pore system is an important scientific issue that must be clarified for large-scale MW-CSS projects. The core of this technology lies in multi-scale refined characterization of reservoirs and evaluation of mechanical properties, revealing the water-rock reaction kinetics mechanism and pore structure evolution law during injection; developing a THMC coupled numerical simulator to carry out simulation optimization and formation risk prediction for efficiency-enhanced processes such as low-damage regulation and modified water-alternating-gas injection, and formulating intelligent injection schemes and regulation strategies adapted to different technical paths of MW-CSS.

Domestic and foreign studies have formed a systematic understanding of the mechanism of traditional storage media represented by sandstone and saline aquifers, that is, the injection of acidic fluids will trigger dissolution-precipitation reactions of reservoir minerals. This process has a dual effect on reservoir physical properties. On the one hand, the dissolution of carbonate and aluminosilicate minerals can locally expand pore space and improve permeability, which is conducive to fluid transport (Zhu et al., 2025; Zou et al., 2024); on the other hand, new minerals (such as calcite, gypsum, and iron-bearing minerals) formed by rapid re-precipitation of dissolved ions tend to clog pore throats (Lin et al., 2026). The two compete and jointly control the dynamic evolution of reservoir injectability. At the same time, mineral dissolution will weaken the mechanical strength of the rock skeleton (Ni et al., 2019), while changes in fluid pressure may alter the in-situ stress field and induce micro-fractures. These mechanical-chemical coupling effects are directly related to caprock integrity. Numerical simulation further reveals the strong spatiotemporal heterogeneity and scale dependence of this process, which shows significant evolution from the early stage (dominated by near-wellbore dissolution and convective transport), the middle stage (spatially differentiated dissolution-precipitation interaction) to the

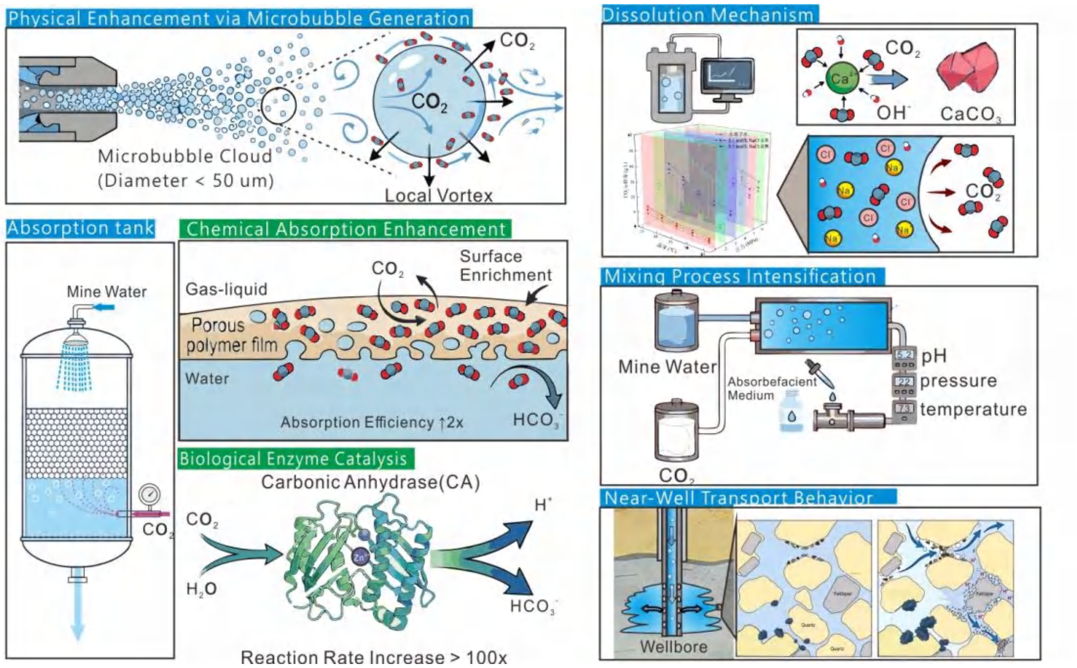

Fig. 2 Key technologies for high-efficiency gas-water mixing

long term (>10^3 years, dominated by large-scale stable mineral carbon sequestration), and the time for the reservoir system to fully reach chemical sequestration equilibrium can reach the millennium scale (Wang et al., 2021).

Carbon sequestration formations in China's coal mining areas generally have low porosity, low permeability, strong heterogeneity, and are located in complex geological environments with high temperature and high pressure. Domestic scholars have confirmed through experiments and simulations that temperature fields (Zhang et al., 2022), ion composition and high salinity characteristics of initial formation water (Meng et al., 2024), and key parameters such as impurity gases (e.g., H_2S, SO_2) dramatically affect mineral reaction paths and rates (He et al., 2022). Meanwhile, although dissolution can increase porosity, it may also lead to a significant decrease in the uniaxial compressive strength of rocks (Jia, 2023; Jiang et al., 2023), highlighting the potential risk of mechanical integrity weakening. In addition, the strong heterogeneity of reservoirs makes it extremely challenging to extrapolate from homogeneous core experiment scales to real site scales.

However, most existing studies are based on NaCl solutions or pure water systems with simple components. When the object is converted to mine water-CO_2 mixed fluid and typical low-permeability heterogeneous reservoirs in China, the complexity of the system increases dramatically, and there are significant gaps in current understanding. For example, the competitive precipitation mechanism of gypsum and calcite caused by the coexistence of high-concentration SO_4^{2-} and Ca^{2+}, the strong spatiotemporal coupling differentiation law of mineral reactions and fluid transport in low-permeability reservoirs, and the cross-scale THMC evolution caused by strong reservoir heterogeneity, still need to be deeply explored.

4.2 Key technologies of multi-field coupling reaction and efficiency-enhanced injection

(1) Multi-scale refined reservoir characterization and mechanical property evaluation of reservoir-caprock

Use multi-scale methods such as CT and SEM to finely characterize the pore-throat structure, mineral spatial distribution, and in-situ mechanical parameters of the target sandstone, and construct a multi-scale three-dimensional digital core and microscopic pore network model of the target reservoir (Jiang et al., 2025). Carry out high-temperature and high-pressure triaxial-fluid displacement coupling tests on reservoir and caprock cores, monitor and analyze the evolution law of rock strength, elastic modulus, and fracture toughness in real time, reveal the damage and fracture mechanism under the coupling of chemical dissolution and stress corrosion, and establish dynamic mechanical stability evaluation criteria for reservoir-caprock (Ding et al., 2026).

(2) Water-rock reaction kinetics and pore evolution evaluation

Use high-temperature and high-pressure flow reaction devices to simulate the long-term displacement process under formation conditions. Combined with multi-scale characterization (CT, SEM-EDS, XRD) of reservoir cores before and after the reaction, quantitatively characterize the dissolution/precipitation rates of different minerals and the spatial distribution sequence of secondary minerals, establish a reactive solute transport model (Li et al., 2024), and realize quantitative prediction of the spatiotemporal evolution law of reservoir porosity and permeability.

(3) Development of THMC fully coupled numerical simulator and optimization of injection process

Develop a THMC full-process numerical simulator coupled with mineral reaction kinetics, multiphase seepage, rock deformation, and heat transfer (Rene et al., 2025). Using this

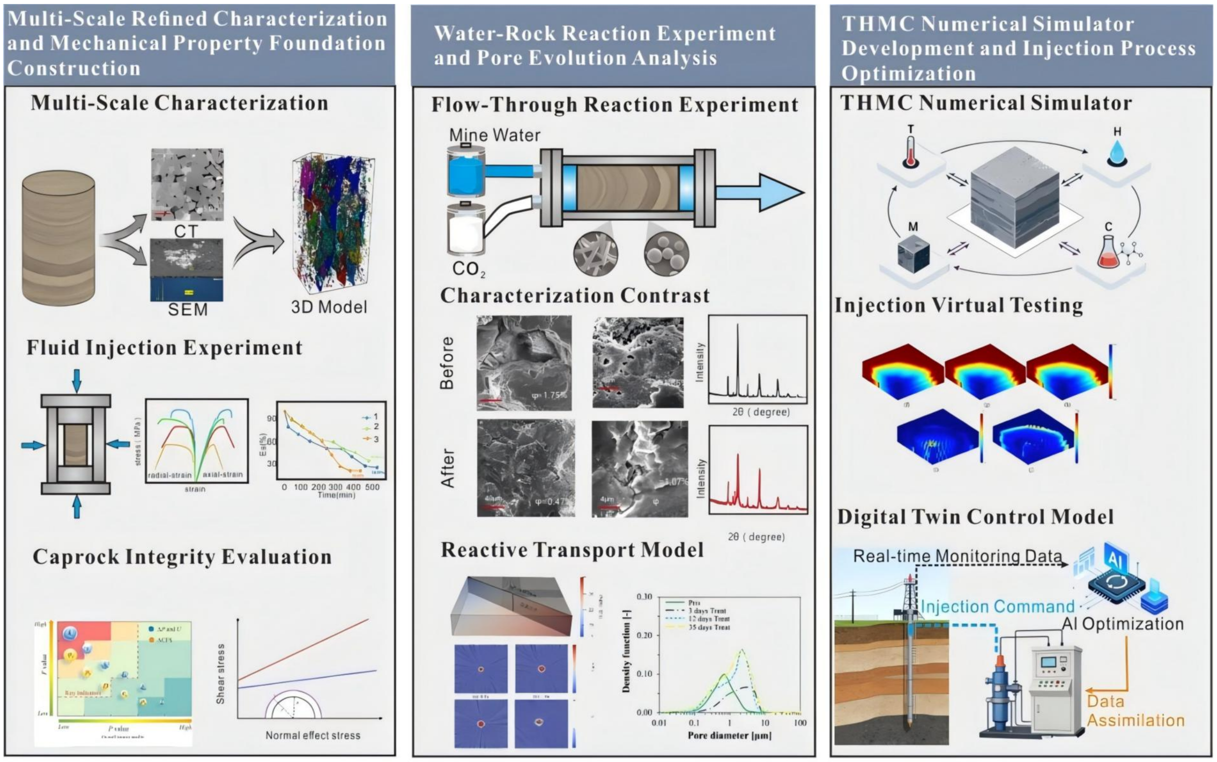

Fig. 3 Key technologies for multi-field coupled reaction and enhanced efficiency injection

simulator, carry out virtual tests on low-damage efficiency-enhanced processes such as mild acidizing plugging removal and water-gas synergistic pulse injection, and form intelligent injection process schemes and digital twin regulation models adapted to low-permeability reservoirs.

5 Multiphase flow corrosion-resistant materials and adaptive safe and efficient injection equipment

Through simulation and laboratory experimental studies on the THMC multi-field coupling mechanism and enhanced injection technology, the reaction evolution of mixed fluids in formations and the safe injection boundary have been clarified. However, the full implementation of the entire process relies on supporting wellbore engineering and high-pressure injection hardware as carriers. To this end, this chapter focuses on corrosion-resistant wellbore structures and customized complete sets of high-pressure injection equipment, aiming to form a hardware technology system for well construction, well completion, and intelligent transportation adapted to mine water-CO_2 multiphase corrosive fluids.

5.1 Research status of materials and injection equipment

Well construction and completion technologies and high-pressure injection equipment are the hardware foundations to ensure long-term injection efficiency and storage safety of MW-CSS projects. For differentiated technical paths derived from different water quality characteristics, mine water rich in multiple ions is highly prone to acidification after absorbing dissolved/supercritical CO_2, and easily forms a strong acidic electrochemical-erosion-abrasion synergistic corrosion environment with high-velocity media (Liu et al., 2026). Meanwhile, high-precision pressure-flow regulation capabilities are required to adapt to differentiated injection strategies for different water qualities. The core of the equipment lies in three aspects: first, through mechanism simulation and experiments, develop differentiated and gradient anti-corrosion materials that can resist multiphase flow corrosion, and realize economically adaptable zonal material selection for the full life cycle of the pipe string. Second, relying on the multi-field coupling evolution model of wellbore integrity, develop a tough wellbore structure integrating corrosion-resistant pipes, flexible sealing components and distributed monitoring. Third, integrate customized high-pressure injection pumps, high-efficiency mixers, intelligent sensing and control systems to form a surface intelligent injection equipment system that can self-adjust according to real-time working conditions and water quality feedback.

In terms of storage well construction and integrity guarantee, domestic and foreign studies emphasize addressing corrosion in CO_2-brine environments by optimizing wellbore structures and high-performance materials, with the focus on the dynamic degradation mechanism of “carbonation-acid dissolution” of cement sheath in CO_2-mine water environments and the thermal-mechanical-chemical (TMC) synergistic failure law (Grimm et al., 2012), as well as casing corrosion laws, and corresponding corrosion inhibitors and monitoring technologies have been developed accordingly (Liu et al., 2024). In terms of high-pressure and large-flow injection pump equipment, the global pump industry is developing towards high efficiency, intelligence and corrosion resistance. International leading enterprises such as Grundfos and KSB have achieved technological breakthroughs in the fields of high-pressure multistage centrifugal pumps and magnetic drive pumps, which can meet the working condition requirements of high-pressure injection, and realize real-time monitoring of flow, pressure and vibration through integrated sensors (Fertl & Chilingarian , 1989).

5.2 Key technologies of materials and injection equipment

(1) Material selection for multiphase flow corrosion resistance

Through computational fluid dynamics-electrochemical coupling simulation and high-pressure dynamic corrosion tests, systematically reveal the influence of key parameters such as flow velocity, gas phase fraction, Cl^- concentration and pH value on the corrosion mechanism of different materials. For high-corrosion scenarios with high-salinity water, develop corrosion-resistant alloys for key parts; for low-salinity water, optimize surface treatment and protection technologies for low-cost modified low-alloy steels (Yanagisawa et al., 2025).

(2) Tough well construction and adaptive safe injection process design

The core of well construction and injection process design is to realize the "gentle" injection of mixed fluids into the deep micro-pore system on the premise of ensuring wellbore integrity on a centennial scale, so as to avoid severe pressure disturbance or damage to the reservoir and caprock. Establish a long-term evolution model of wellbore integrity multi-field coupling covering chemical corrosion-mechanical load-thermal stress, quantitatively evaluate the failure risk under different fluid combinations (Wang et al., 2026), and develop a safe anti-seepage wellbore structure and high-pressure wellhead device based on underground aquifer protection.

(3) System integration of surface intelligent injection equipment for synergistic storage

Based on the mixing enhancement mechanism, simulate and obtain the operating status of equipment during injection, monitoring and protection, determine the core parameters of key equipment, and adopt new composite materials and advanced manufacturing processes to develop customized injection pump equipment with large flow rate, corrosion resistance and high pressure. Integrate modular units such as mixing, pressurization, metering and filtration, combine sensor technology, automatic control technology and data communication technology, and develop an adaptive regulation system based on real-time feedback of pressure, flow, temperature and fluid properties (Xu et al., 2026).

6 MW-CSS potential and multi-factor coupling evaluation technology

On the basis of tackling key engineering hardware technologies such as corrosion-resistant wellbore structures and complete sets of high-pressure intelligent injection equipment, the full-process implementation paths of MW-CSS fluid preparation, formation multi-field reactions, and downhole transportation have been clarified. However, before the technology is implemented, quantitative assessment work such as site screening, storage capacity calculation, and economic and environmental risk prediction must be completed to support the planning and scheme decision-making of demonstration projects in mining areas. To this end, this chapter constructs a multi-factor coupling comprehensive evaluation technology system adapted to the carbon-water synergistic system, forming a complete set of quantitative evaluation methods and intelligent decision-making tools from the three dimensions of storage potential, system risk, and full-cycle benefit.

6.1 Research status of MW-CSS potential evaluation

Scientific evaluation of the storage potential, comprehensive benefits, and long-term risks of MW-CSS is an indispensable prerequisite for its large-scale planning and project decision-making. Its evaluation needs to simultaneously quantify the physical dissolution and chemical mineralization of CO_2, as well as the safe elastic acceptance capacity of the formation for pore pressure of mine water reinjection; at the same time, it is necessary to integrated accounting of carbon emission reduction benefits, mine water treatment cost savings, cost hedging brought by infrastructure sharing, and environmental synergy values. Therefore, the core of the technology lies in constructing a dynamic evaluation framework that runs through "mechanism-potential-risk-benefit" and can adapt to different technical paths. First, quantify the core performance indicators under different synergistic paths; second, calculate the comprehensive storage potential of the "water-carbon" binary system; third, comprehensively reveal the economic feasibility and environmental risk boundaries of the project; finally, establish an intelligent site selection and decision support system to realize intelligent decision support throughout the process from regional screening, path optimization to scheme comparison.

In the field of CO_2 geological storage, domestic and foreign studies have established a mature and systematic site selection evaluation system. Led by research from institutions such as the Carbon Sequestration Leaders Forum (CSLF), the International Organization for Standardization (ISO), and the U.S. National Energy Technology Laboratory (NETL), the evaluation dimensions have fully covered geological safety, storage potential scale, engineering injectability, environmental and socio-economic risks, etc. Site selection research has developed from single geological condition judgment to comprehensive evaluation with multi-disciplinary coupling. Bachu2003, Oldenburg et al. (2019) and Grataloup et al. (2009) respectively proposed first-level indicator frameworks centered on basin characteristics, basic storage potential and secondary trapping capacity, and storage-risk-regulation, and realized quantitative and semi-quantitative comparison through methods such as weighting and superposition, laying the methodological foundation for site selection work. Akbarian et al. (2026) studied the evaluation indicators and method models of mine water geological storage. These studies together present a clear orientation of "taking geological safety as the core, and attaching equal importance to technical and economic feasibility and social acceptability". However, the evaluation of MW-CSS faces threefold new challenges: complicated storage mechanisms (coexistence of physical dissolution and chemical mineralization), diversified benefit sources (carbon emission reduction, water treatment cost savings, environmental synergy), and technology path dependence (evaluation results vary with water quality and process selection).

6.2 Key technologies of MW-CSS potential evaluation

(1) Dynamic comprehensive evaluation model of "mechanism-potential-risk"

Through systematic screening of key indicators, quantitatively characterize the core attributes of the reservoir formation under different technical paths, such as phase state conversion efficiency, mineral fixation rate, effective storage space, caprock integrity, and groundwater impact, and construct an evaluation model of "storage mechanism - storage potential - system risk" for MW-CSS.

(2) Calculation method of differentiated synergistic storage potential

Based on the calculation of dissolved CO_2 capacity under changes in formation temperature-pressure field and salinity field, evaluate its dissolution trapping effect and the limit of multiphase diffusion migration (Rezk & Ibrahim, 2026), construct a mineral storage calculation model under the constraint of multi-ion reaction kinetics, and form a differentiated synergistic storage calculation and prediction method based on water quality types and geological conditions.

(3) Full-cycle multi-dimensional benefit-cost-risk coupling evaluation

Establish a full life-cycle cost-benefit analysis model, and conduct refined accounting of hedging benefits such as reducing per-ton carbon cost, value-added benefits such as water treatment fee savings and potential carbon credits generated compared with the separate implementation of CO_2 geological storage (CGS) and deep geological disposal of mine water (GDWIS). Through sensitivity analysis, analyze the feasible critical carbon price, water price, and key geological parameter thresholds of the project. At the level of environmental risks, evaluate the long-term transformation of reservoir pore structure by mineral precipitation and potential plugging risks, the long-term migration range of dissolved CO_2 and the potential impact of slow acidification on surrounding rocks, and simulate the occurrence probability and environmental consequences of different leakage scenarios (Alshammari et al., 2022).

(4) Intelligent site selection and decision support system with multi-factor synergy

Develop an intelligent site selection and decision support system for MW-CSS based on the risk evaluation model, differentiated potential calculation methods, and multi-dimensional coupling evaluation modules. The system has a progressive analysis process of "preliminary screening - detailed evaluation - comparison and selection - optimization", and has the function of recommending suitable technical paths. At the same time, it can visually display the spatial distribution of storage potential and risks, and simulate the full-cycle benefits under different process schemes.

7 Physicochemical signal response mechanism and efficient monitoring technology of MW-CSS

The multi-factor coupling evaluation system of MW-CSS established in the previous chapters can complete storage potential calculation, site screening, and full-cycle risk-benefit assessment. However, dynamic hidden dangers such as formation fluid migration, wellbore corrosion and leakage, and reservoir structure evolution during the long-term operation of the project cannot be identified in real time by static evaluation methods. To this end, this chapter relies on the natural tracing advantage of high conductivity of mine water to construct a complete set of technologies for multi-field signal identification, full-domain three-dimensional monitoring, and intelligent early warning, forming a dynamic monitoring system covering the entire storage cycle to ensure the long-term safe operation of MW-CSS projects.

7.1 Research status of monitoring technology

Comprehensive, real-time, and accurate monitoring and early warning of the storage process is the key to ensuring the long-term safety of MW-CSS and verifying its scientific effectiveness. The introduction of mine water in MW-CSS fundamentally changes the physical basis of monitoring. Its high salinity characteristic provides a natural "conductive tracer" for directly and economically characterizing the migration of mixed fluids using geophysical methods such as electromagnetic methods, making it possible to develop high-sensitivity, low-cost specific monitoring technologies. Monitoring technology includes four core research directions: first, the multi-physical field signal response mechanism induced by CO_2-mine water-rock interaction; second, special monitoring technology for wellbore integrity; third, the "space-air-ground-well" full-domain three-dimensional collaborative monitoring system; fourth, an integrated platform for intelligent early warning and emergency decision-making driven by machine learning.

In the traditional CCS field, time-lapse seismic has ambiguity in its sensitivity to changes in formation elastic modulus and wave impedance, and faces limitations of high cost and shielding by high-resistance caprocks in large-scale continuous monitoring (Lumley, 2001); Represented by large-scale demonstration projects such as Sleipner in Norway, Weyburn in Canada, and In Salah in Algeria, foreign countries have constructed a multi-dimensional technical system centered on time-lapse seismic, vertical seismic profiling, electrical resistance tomography, and surface deformation InSAR monitoring, realizing dynamic description and long-term tracking of CO_2 plume spatial distribution, migration front, and caprock integrity (Amer et al., 2025); In demonstration projects such as Shenhua CCS and Jilin Oilfield in China, a comprehensive monitoring system integrating VSP, surface deformation monitoring, groundwater chemical analysis, and soil gas flux monitoring has been established (Tang et al., 2025); In recent years, new technologies such as microseismic monitoring, distributed optical fiber sensing, and wide-field electromagnetic method have been gradually applied to deep fluid migration monitoring, showing advantages of high sensitivity and real-time performance in capturing mine water flow behavior and identifying micro-fracture channels (Ozer & Toker, 2013).

For complex media environments such as mine water, real-time tracking of the fluid front is achieved through the coupling of microseismic and optical fiber sensing, the spatial distribution of CO_2 in aquifers is reconstructed based on wide-field electromagnetic inversion (Zhu et al., 2016), and the fusion and calibration of multi-source monitoring information with data assimilation and machine learning methods is the current research frontier (de la Cruz-Azuara et al., 2026); However, how to construct a dedicated monitoring technology system from signal mechanism to intelligent early warning for the nonlinear resistivity mutation and dielectric anomaly of rocks triggered by the alternating migration of salt-rich conductive water phase and highly insulating CO_2 gas/liquid two-phase in MW-CSS remains a key problem to be solved urgently.

7.2 Key monitoring technologies

(1) Multi-physical field signal response mechanism and joint inversion of storage process

Through laboratory autoclave experiments and multi-field coupling numerical simulation, systematically study the generation mechanism and spatiotemporal evolution law of key signals such as geochemical ion concentration mutation, microseismic events, resistivity anomalies, and distributed optical fiber strain response associated with this process. On this basis, form a collaborative deployment scheme and joint inversion algorithm of microseismic, distributed optical fiber acoustic sensing, and wide-field electromagnetic method, and perform constrained inversion of multiple parameters such as vibration, strain, and resistivity under a unified geological model framework (Zhang et al., 2016), significantly improving the dynamic imaging accuracy of fluid migration front, pressure disturbance, and reservoir volume change.

(2) Special monitoring technology for wellbore integrity

Construct a “point-line-plane” integrated wellbore integrity monitoring technology system: at the “point” level, develop downhole sensors based on ultrasonic or electromagnetic principles for monitoring corrosion and micro-leakage at key parts such as casing couplings and packers; at the “line” level, deploy a distributed optical fiber sensing (DOFS) network to continuously monitor the longitudinal temperature and acoustic vibration signals of the wellbore, realizing rapid location of leakage points; at the “plane” level, evaluate the influence range of cement sheath integrity failure on surrounding formations combined with cross-well electrical or microseismic monitoring.

(3) “Space-air-ground-well” full-space collaborative monitoring system

To achieve three-dimensional transparent monitoring from injection wells to shallow surface, it is necessary to establish a multi-scale and multi-platform collaborative monitoring network. Design and integrate the “space-air-ground-well” four-dimensional monitoring scheme: use space-based InSAR technology to monitor large-scale surface deformation; conduct regional scanning through air-borne airborne geophysical exploration; lay high-density electrical method and soil gas monitoring points on the ground; finally achieve deep integration with downhole optical fiber, geochemical and other data. Formulate spatiotemporal synchronous acquisition schemes for multi-source data, unified transmission protocols and standardized data interfaces to form three-dimensional monitoring capabilities covering the entire storage cycle.

(4) Big data-based intelligent early warning and decision support system

Based on historical data, simulation results and expert knowledge, construct a hierarchical and classified risk early warning index system covering multiple types of parameters such as pressure anomalies, microseismic activity, and groundwater chemical mutations. Use machine learning algorithms to establish a dynamic risk early warning model to realize automatic identification of different risk levels. Finally, develop an intelligent emergency plan database and decision support module linked to the early warning level. Once an early warning is triggered, the system can automatically generate a response plan including preliminary location of leakage points, estimation of influence range, and emergency well shut-in procedures.

8 Core processes and application promotion models of mine water-CO_2 synergistic sequestration

8.1 Core process paths

To achieve safe, efficient, and controllable co-disposal of MW-CSS from concept to engineering practice, based on a deep understanding of the complexity of CO_2-water-rock interactions, precise control of the phase state and mixing position of mixed fluids is required in engineering to optimize the sequestration effect and manage risks. Based on the position where mixing occurs and the logic of phase state control, this study proposes and analyzes the following three technology paths with clear innovation orientation.

(1) Surface Pre-Dissolution Injection

By constructing a high-pressure mixing system on the surface integrating multiple means such as micro/nano bubble generation, vortex-enhanced mass transfer, and chemical catalysis, CO_2 is dissolved in mine water as much as possible to prepare a “CO_2-rich sequestration aqueous solution” with uniform properties and dominated by a single liquid phase, which is then injected underground. This changes the traditional method of injecting supercritical CO_2 underground, and significantly mitigates complex migration problems such as buoyancy-driven flow, gas channeling, and interfacial tension caused by gas-phase plumes from the physical root (Figure 5a). The greatest advantage of this method is that it fundamentally guarantees the geological safety and predictability in the initial stage of injection. Simulation studies have shown that the injection of high-density CO_2-saturated brine can produce negative or neutral buoyancy, greatly enhancing the stability of the sequestration body, and making it possible to implement large-scale sequestration in areas with complex structures or where caprock integrity is sensitive. This method is suitable for large-scale disposal of large volumes of mine water and small amounts of CO_2, or as a demonstration technology in high-risk areas. The success of the CarbFix project in Iceland has verified the feasibility of its technical logic (Matter et al., 2016).

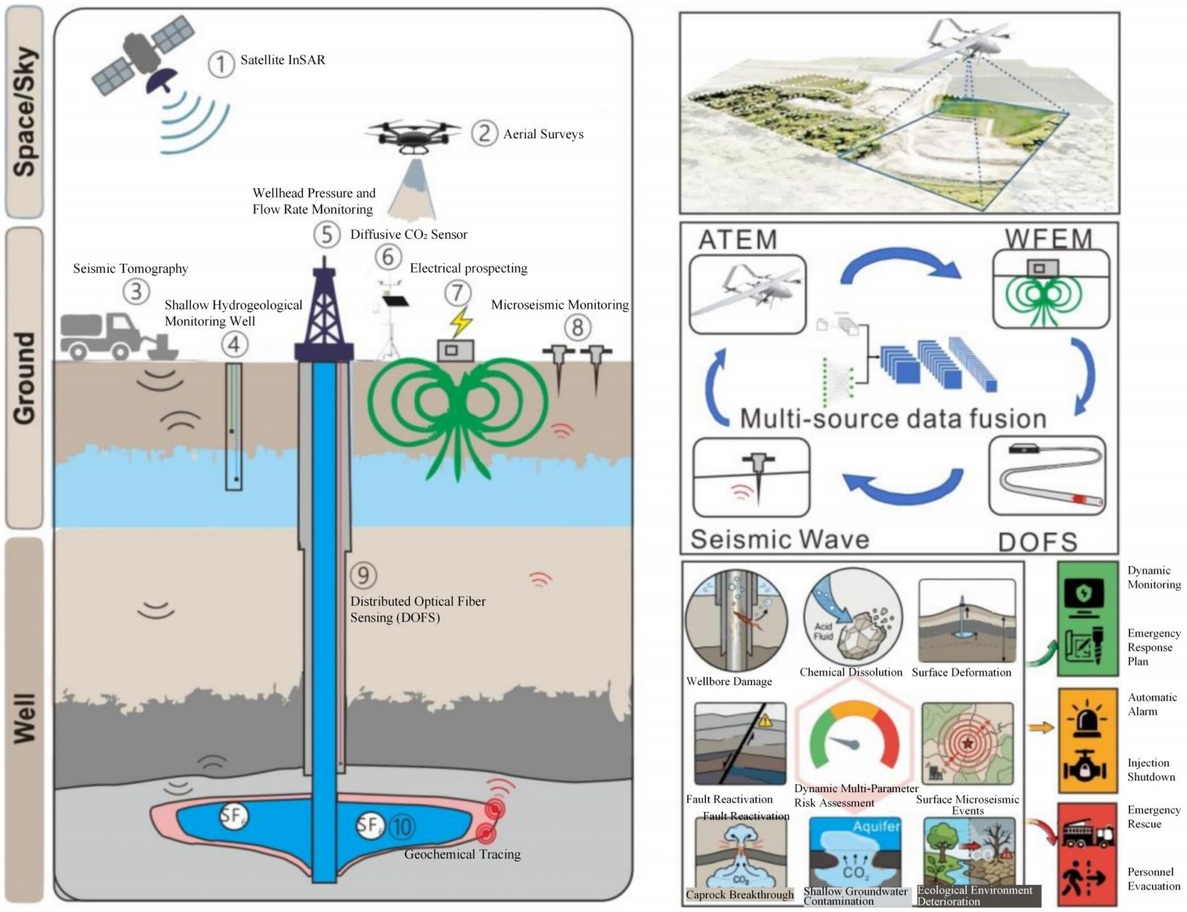

Fig. 4 Key monitoring technologies for MW-CSS

Two aspects still need to be improved for the engineering application of this path. The first is to improve the efficiency of surface mixing and the solubility limit: through multiple strengthening means such as physical, chemical, or biological methods, maximizing the dissolution amount and dissolution rate of CO_2 under a given economic pressure is a key technical issue, and finally a relationship model of mixing efficiency, energy consumption, and final solubility will be established. The second is to prevent phase state instability and desorption risks during the injection process: by studying the phase state evolution law of the mixed fluid, it is ensured that the dissolved CO_2 will not desorb due to pressure reduction or temperature rise under the temperature and pressure trajectories of the mixed fluid in the wellbore and formation, so as to prevent gas lock in the wellbore or near-wellbore area, which would affect the injection capacity.

(2) Water-Alternating-Gas Injection

Drawing on enhanced oil recovery technologies in oil and gas fields, mine water slugs and supercritical CO_2 are injected successively through the same injection well. By regulating the injection sequence, injection volume, and alternating cycle of mine water and CO_2, the two are mixed and react inside the reservoir (Figure 5b). Relevant research results show that this mechanism can reduce the CO_2 saturation at the top of the reservoir by up to 50%, which not only improves the dissolution sequestration reaction capacity but also creates a more uniform distribution environment for subsequent mineralization reactions. At the same time, this process has relatively simple requirements for surface facilities, does not require a complex surface mixing system, and has certain convenience for engineering implementation. The water slug injected in water-alternating-gas injection can displace and disperse the CO_2 at the front, reduce the CO_2 saturation at the top of the reservoir, thereby inhibiting gas channeling, forcing CO_2 to enter more pore spaces, and increasing its contact area with formation water and rocks (Rathnaweera et al., 2016; Wu et al., 2026). This method is applicable to blocks with thick reservoirs, moderate heterogeneity, and certain basic well pattern conditions. For high-salinity mine water, through intelligent alternating injection, it is expected to regulate the mineralization reaction to occur in the deep part of the reservoir rather than the near-wellbore area, making it one of the mainstream processes with significant potential.

For the engineering application of this path, the following aspects need to be prioritized for improvement. First, through laboratory experiments, observe and quantify the displacement efficiency and gas-water distribution characteristics under different injection schemes, further simulate the hysteresis effect of relative permeability in heterogeneous media and the influence of gravity differentiation of non-uniform fluids at the reservoir scale, and carry out large-scale parameter optimization studies on key parameters such as slug size, injection rate, and alternating cycle. Second, introduce interval fine monitoring and intelligent dynamic regulation means. By conducting real-time monitoring in injection wells and monitoring wells to obtain changes in temperature and acoustic signals, identify signs of gas-water migration, stratification, or gas channeling. Dynamically optimize the dynamic alternating injection strategy with the help of machine learning algorithms.

(3) In-Wellbore Synergistic Injection

In this process, CO_2 and mine water are synchronously injected underground through the wellbore. Relying on the geothermal gradient, the two fluids continuously intensify their mixing under the gradual change of temperature and pressure conditions of deep formations, and achieve full dissolution before reaching the reservoir or upon entering the reservoir, forming a highly dispersed system with water as the continuous phase (Figure 5c). Compared with the surface pre-mixing method, this path significantly reduces the dependence on high-pressure surface mixing facilities, and at the same time shortens the residence time of CO_2-saturated liquid in high-pressure pipelines, thereby reducing the risk of desorption caused by temperature and pressure fluctuations. In addition, this process supports one-way continuous injection, which helps to reduce the risk of two-phase separation in surface multiphase gathering and transportation systems, and alleviates the gas channeling lock and water lock effects triggered by sudden phase changes in the near-wellbore area of the reservoir, presenting good flexibility in engineering implementation. This path achieves a good balance between technical risks and investment costs, and is suitable as a preferred solution for the transformation of old oilfields or the initial stage of technology demonstration.

Although the in-wellbore synergistic injection is simpler in the process, it still needs to enhance the precise control of downhole mixing efficiency and dissolution degree. By establishing a full-wellbore multiphase flow and mass transfer coupling experimental device, simulate real wellbore conditions, predict the phase state and dissolution degree at different depths, study the flow pattern evolution and dissolution efficiency under different injection parameters, and control the injection flow rate, pressure, and temperature of the two fluids in the wellbore, so that they reach a fully dissolved state when entering the reservoir, and prevent the formation of large-scale free gas slugs. On the other hand, develop reliable wellbore integrity guarantee devices to prevent acid corrosion and gas leakage in the wellbore, and identify abnormal conditions and automatically shut down through the monitoring and intelligent control system to ensure injection safety.

8.2 Application and promotion model

(1) Integration of full-chain technical solutions and construction of standardized modules

Based on previous studies on mechanisms, equipment, monitoring and evaluation, scattered technical achievements are seamlessly connected and systematically optimized to form a set of standardized, modular and reusable full-chain technical solutions. The core is to build four technical module packages covering “fluid treatment - mixed injection - monitoring and early warning - comprehensive evaluation”.

(2) Demonstration project verification and iterative optimization path

It is planned to carry out comparative full-chain demonstrations in typical mining areas to verify the process systems centered on low-salinity water and high-salinity water respectively. During an injection period of no less than 2 years, full-dimensional data such as engineering parameters, monitoring signals and core drilling samples will be systematically collected to build a dedicated database. Using these real data, inversion, calibration and optimization are carried out for all the aforementioned mechanism models, evaluation models and control algorithms, forming a closed-loop feedback mechanism of “demonstration verification - data-driven - model iteration - technology upgrading”, which greatly improves the reliability and universality of the technical system.

(3) Promotion and application model and industrial ecosystem construction

At the technical level, a cloud-based Decision Support System (DSS) will be developed to provide users with online services from initial potential assessment to scheme design. In terms of business models, models such as bundled trading of “carbon-water” environmental rights and interests and BOO (Build-Own-Operate) are designed. At the policy level, it is recommended to formulate MW-CSS project certification methodology, promote the inclusion of its emission reductions and discharge volumes into the carbon market and emission rights trading system, and enjoy green financial support. Ultimately, an industrial ecosystem driven by the synergy of technology, market and policy will be constructed.

9 Conclusions and prospects

9.1 Conclusions

(1) The scientific connotation and technical adaptability of MW-CSS are clarified, and the core concept of “synergistic co-treatment of wastes and realizing synergistic value increment” is established. MW-CSS leverages the natural synergistic foundation in site selection evaluation, engineering construction, monitoring and early warning between CGS and GDWIS in major coal-producing areas. It breaks through the traditional single-storage thinking, transforming mine water from a passively disposed object into an active medium that actively drives CO_2 mineralization. This achieves triple optimization of improved storage efficiency, reduced safety risks, and offset environmental protection costs, providing a new technical path to solve the dual challenges of “emission reduction” and “pollution control” in coalfield areas.

(2) The key scientific issues and mechanism basis of MW-CSS in deep low-permeability reservoirs in coalfields are revealed. It is clarified that the primary pore system of deep sandstone serves as the main storage space, with “non-fracturing” controlled-rate injection as the core feature. A key technology cluster covering the entire MW-CSS chain has been formed, including: differentiated mixed fluid preparation and phase state regulation technology, path-dependent multi-field coupling simulation and mild efficiency-enhanced injection technology, corrosion-resistant intelligent equipment technology, multi-

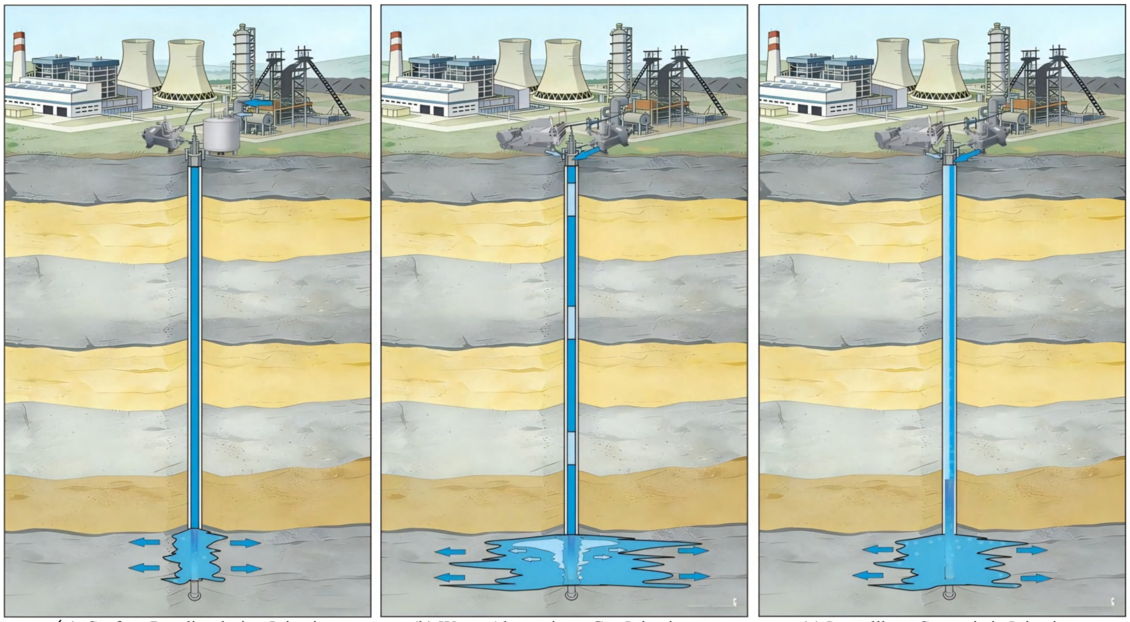

Fig. 5 Three core injection process route of MW-CSS

factor coupling dynamic evaluation technology, and multi-physical field integrated intelligent monitoring technology.

(3) A full-chain technical system framework for MW-CSS covering “efficient mixing - efficiency-enhanced injection - equipment - monitoring and early warning - comprehensive evaluation” is proposed. Three core injection process paths adapted to low-permeability coalfield reservoirs, namely “surface pre-dissolution - water-alternating-gas injection - in-wellbore synergy”, are established, and an efficiency-enhanced injection parameter combination based on flow field optimization is put forward.

(4) The engineering application value and promotion path of MW-CSS in coalfield areas are clarified. Through the mechanisms of “cost offset” and “facility sharing”, MW-CSS is expected to significantly reduce the marginal cost of per-ton carbon sequestration to a commercially feasible range. It not only solves the two major problems of carbon emission reduction and high-salt wastewater disposal simultaneously, but also is expected to promote the transformation of traditional energy resource-based regions into comprehensive “zero-carbon park” service bases that provide carbon sink credits, environmentally friendly and safe disposal, providing an industrial solution with both environmental and economic benefits for the country’s “double carbon” goals and regional green transformation.

9.2 Prospects

(1) Carry out full-process industrial-scale demonstration: It is urgent to launch a full-process demonstration project of 1 million tons of mine water + 50,000 tons of CO_2 in a typical mining area to verify the engineering feasibility, long-term safety, storage efficiency and full-life-cycle economy of the technical path, and obtain valuable on-site data.

(2) Deepen ultra-long-term safety and mechanism research: It is necessary to develop a more accurate long-time-scale fully coupled thermal-hydro-mechanical-chemical prediction model, and carry out geological analog site research to empirically verify the ultra-long-term stability of the storage body. At the same time, it is necessary to further reveal the microscopic mechanism of competitive reactions in complex ion systems.

(3) Accelerate the construction of standards, specifications and policy systems: Promote the formulation of dedicated technical standards, environmental assessment guidelines, monitoring specifications and safety supervision frameworks for MW-CSS. Actively study the methodology for incorporating its emission reductions into the national carbon market (C-CER), explore new business models such as bundled trading of “carbon-water” environmental rights and interests, and build a dual-driven mechanism of policies and markets to promote industrial development.

(4) Expand technology coupling and comprehensive application: Explore the synergistic coupling of MW-CSS with technologies such as geothermal energy development (CO_2-EGS), strategic mineral storage, and underground hydrogen storage, expand its comprehensive value as a multi-resource synergistic underground space utilization platform, and serve the national energy and resource security strategy.

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Conflict of interest

The authors declare no competing interest.

References

Akbarian M, Saghafian B, Golian S. 2023. Monthly streamflow forecasting by machine learning methods using dynamic weather prediction model outputs over Iran. *Journal of Hydrology*, **620**(B): 129480. doi:10.1016/j.jhydrol.2023.129480.

Alshammari A, Lakshmi V, Brantley D, et al. 2022. Simulation of carbon dioxide mineralization and its effect on fault leakage rates in the South Georgia rift basin, southeastern U.S. *Heliyon*, **8**(6): e09635. doi:10.1016/j.heliyon.2022.e09635.

Amer R, Xue ZQ, Hashimoto T, et al. 2025. Strain analysis for early leakage detection and geomechanical monitoring at CO_2 storage sites using distributed fiber optic strain sensing. *Fuel*, **384**: 133937. doi:10.1016/j.fuel.2024.133937.

Baba I A, Mustapha S, Awe O B, et al. 2026. Zero-valent iron-based nanomaterials as sustainable catalysts for the sequestration of emerging contaminants in wastewater: Mechanisms, performance, and challenges. *Inorganic Chemistry Communications*, **191**: 117231. doi:10.1016/j.inoche.2026.117231.

Bachu S. 2003. Screening and ranking of sedimentary basins for CO_2 storage in geological media in Canada. *Environmental Geology*, **44**(1): 70–81. doi:10.1007/s00254-003-0762-9.

Chapoy A, Mohammadi A H, Chareton A, et al. 2004. Measurement and modeling of gas solubility and literature review of the properties for the carbon dioxide−water system. *Industrial & Engineering Chemistry Research*, **43**: 1794–1802. doi:10.1021/ie034232t.

Chai J, Li Y F, Li S M, et al. 2025. Applications and prospects of nanomaterials for enhanced geological CO_2 sequestration: A review. *Alexandria Engineering Journal*, **123**: 425–435. doi:10.1016/j.aej.2025.03.094.

de la Cruz-Azuara J E, El Hamzaoui Y, Sanchez M A. 2026. Machine learning for CO_2 geological storage and CO_2-enhanced oil recovery in hydrocarbon reservoirs: A critical review of methodologies, the sim-to-real gap, and a roadmap for field-scale deployment. *Results in Engineering*, **30**: 110928. doi:10.1016/j.rineng.2026.110928.

Ding W J, Zhe H C, Liu S Q, et al. 2026. Pore structure damage and mechanical response law of shale under impact load. *Mineralogy and Petrology*, **46**: 258–271. doi:10.19719/j.cnki.1001-6872.2026.01.19.

Du S, Xie Z Q, Li X, et al. 2025. Geological Deep Well Injection and Storage Technology under the “Dual Carbon” Goals: Advances, Challenges, and Prospects. *Coal Geology of China*, **37**(12): 1–11+44. doi:10.3969/j.issn.1674-1803.2025.12.01.

Du S, Li X, Che Q H, et al. 2026. Technical system and engineering application of deep geological storage for coal mine water. *Journal of China Coal Society*, **51**(S1): 344–363. doi:10.13225/j.cnki.jccs.2025.0974.

Du T, Yao HY, Pei GH, et al. 2026. Research Status and Prospects of Coal Mine Underground Reservoirs in China. *GeoStorage*, **2**(3): 196–215. doi:10.46690/gs.2026.03.01.

Eke P E, Naylor M, Haszeldine S, Curtis A. 2011. CO_2/brine surface dissolution and injection: CO_2 storage enhancement. *SPE Projects, Facilities & Construction*, **6**: 41–53. doi:10.2118/124711-PA.

Fertl WH, Chilingarian GV. 1989. Chapter 15 Evaluation and Monitoring of Enhanced Oil Recovery Projects Based on Geophysical Well Logging Techniques. *Developments in Petroleum Science*, **17B**: 451–494. doi:10.1016/S0376-7361(08)70467-9.

Furre AK, Eiken O, Alnes H, et al. 2017. 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia*, **114**: 3916–3926. doi:10.1016/j.egypro.2017.03.1523.

Gao RS, Sun AY, Nicot JP. 2016. Identification of a representative dataset for long-term monitoring at the Weyburn CO_2-injection enhanced oil recovery site, Saskatchewan, Canada. *International Journal of Greenhouse Gas Control*, **54**: 454–465. doi:10.1016/j.ijggc.2016.05.028.

Ghiasi M, Eghtedari H S, Gholami S, et al. 2026. Green CO_2-capture cluster model using bioengineering of carbonic anhydrase enzyme: QM and QM′ approach. *Scientific Reports*, **16**: 2806. doi:10.1038/s41598-025-32638-y.

Grataloup S, Bonijoly D, Lahann H, et al. 2009. A site-selection methodology for CO_2 underground storage in deep saline aquifers. *Energy Procedia*, **2009**(1): 2929–2936. doi:10.1016/j.egypro.2009.02.068.

Grimm RP, Eriksson KA, Ripepi N, et al. 2012. Seal evaluation and confinement screening criteria for beneficial carbon dioxide storage with enhanced coal bed methane recovery in the Pocahontas Basin, Virginia. *International Journal of Coal Geology*, **90–91**: 110-125. doi:10.1016/j.coal.2011.11.002.

Guo H Y, Zhao J, Liu P Y. 2018. Strength softening characteristics and chemical analysis of deep soft rock after water interaction. *Chinese Journal of Rock Mechanics and Engineering*, **37**: 3462–3469. doi:10.13722/j.cnki.jrme.2017.1178.

He XQ, Tian XH, Song DZ. 2022. Research progress and prospect of safe CO_2 storage in coal seams. *Coal Science and Technology*, **50**: 212–219. doi:10.13199/j.cnki.cst.2021-0843.

IEA. 2024. CCUS in Clean Energy Transitions 2024. International Energy Agency.

Jia LH. 2023. Brief discussion on research status of carbon dioxide capture and storage processes. *Leather Manufacture and Environmental Technology*, **4**: 166–168. doi:10.20025/j.cnki.CN10-1679.2023-18-56.

Jiang SH, Shi SZ, Zhao K, et al. 2023. Exploration prospect and development direction of deep coal and coalbed methane. *Science & Technology Review*, **41**: 106–113. doi:10.3981/j.issn.1000-7857.2023.07.011.

Jiang L L, Tian L, Chen Z X, et al. 2025. Research on the micropore structure and multiscale fractal characteristics of shale under supercritical CO_2 action: A case study of the Chang 7_3 sub-member in the Ordos Basin. *Natural Gas Geoscience*, **36**: 533–553. doi:10.11764/j.issn.1672-1926.2024.09.005.

Juanes R, Spiteri EJ, Orr FMJr, Blunt MJ. 2006. Impact of relative permeability hysteresis on geological CO_2 storage. *Water Resources Research*, **42**: W12418. doi:10.1029/2005WR004806.

Koide H, Tazaki Y, Noguchi Y, et al. 1992. Subterranean Containment and Long-Term Storage of Carbon Dioxide in Unused Aquifers and in Depleted Natural Gas Reservoirs. *Energy Conversion and Management*, **33**: 621–628. doi:10.1016/0196-8904(92)90064-4.

Li YM, Pang ZH, Li J, et al. 2012. CO_2 sequestration and utilization in deep saline aquifers. *Science and Technology Review*, **36**: 70–79. doi:10.3969/j.issn.1672-3791.2012.36.049.

Li Q, Zhao N, Liu LC, et al. 2019. Environmental risk assessment method for Australian Gorgon CO_2 saline aquifer storage project. *Environmental Engineering*, **37**: 22–26. doi:10.13205/j.hjgc.201902003.

Li YD, Ding SW, Zhang M, et al. 2024. Sensitivity analysis of injection-production parameters for CO_2 flooding and storage in low-permeability reservoirs considering sequestration mechanisms. *Xinjiang Petroleum Geology*, **45**: 711–718. doi:10.13873/j.cnki.cn65-1107/oil.2024.06.007.

Li YB, Chen YW, Zhao JZ, et al. 2024. Interaction mechanism between supercritical carbon dioxide and shale. *Oil & Gas Geology*, **45**: 1180–1194. doi:10.11743/ogg20240420.

Lin QG, Zhang SJ, Wang XZ, et al. 2019. Establishment of monitoring system for CO_2 flooding and storage in low and ultra-low permeability reservoirs. *Journal of Safety and Environment*, **19**: 693–703. doi:10.13637/j.issn.1009-6094.2019.02.047.

Lin X, Li Z, Liu LW, et al. 2026. Regulation and modification mechanism of shale reservoirs by supercritical carbon dioxide. *Natural Gas Geoscience*, **37**(6): 1230–1248. doi:10.11764/j.issn.1672-1926.2025.11.007.

Liu SN, Zhang LW, Su XB, et al. 2020. Review on modeling and parameter selection for chemical reactions of mineral dissolution and precipitation under the condition of CO_2 sequestration. *Water Resources and Hydropower Engineering*, **51**: 13–22. doi:10.13928/j.cnki.wrahe.2020.11.002.

Liu XX, Zeng YF, Wu Q, et al. 2024. Ecological-Based Mining: A Coal–Water–Thermal Collaborative Paradigm in Ecologically Fragile Areas in Western China. *Engineering*, **38**: 209–222. doi:10.1016/j.eng.2024.01.019.

Liu MX, Wang L, Chen WY, et al. 2026. Transformation mechanisms of elements and structure in low-rank coal under acidic/alkaline mine water-ScCO_2 interaction: Implications for CO_2 sequestration in abandoned coal mines. *Journal of Environmental Chemical Engineering*, **14**(13):122784. doi:10.1016/j.jece.2026.122784.

Lumley DE. 2001. Time-lapse seismic reservoir monitoring. *Geophysics*, **66**(1): 50–53. doi:10.1190/1.1444921.

Matter JM, Stute M, Snæbjörnsdóttir SÓ, et al. 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, **352**: 1312–1314. doi:10.1126/science.aad8132.

Meng HL, Yang WF, Wang B, et al. 2024. Study on feasibility and storage model of carbon dioxide landfill in goafs of deep coal seams. *Shanxi Coal*, **44**: 1–7. doi:10.3969/j.issn.1672-5050.2024.03.001.

Ni HJ, Guo X, Ding L, et al. 2019. Experiment on the effect of supercritical carbon dioxide immersion on mechanical properties of shale. *Journal of China University of Petroleum (Edition of Natural Science)*, **43**: 77–84. doi:10.3969/j.issn.1673-5005.2019.02.009.

Oldenburg CM, Bryant SL, Nicot JP. 2019. Certification framework for geologic carbon sequestration. *International Journal of Greenhouse Gas Control*, **3**(4): 444–457. doi:10.1016/j.ijggc.2009.02.009.

Ozer CK, Toker V. 2013. Calcareous Nannoplankton Biostratigraphy of the Bartin Province, Western Black Sea, Turkey. *Acta Geologica Sinica (English Edition)*, **86**(6): 1434–1446. doi:10.1111/1755-6724.12012.

Paluszny A, Graham CC, Daniels KA, et al. 2020. Caprock integrity and public perception studies of carbon storage in depleted hydrocarbon reservoirs. *International Journal of Greenhouse Gas Control*, **98**: 103057. doi:10.1016/j.ijggc.2020.103057.

Pan D, Yao Y, Huang X, et al. 2025. Unveiling hidden reaction kinetics of carbon dioxide in supercritical aqueous solutions. *Proceedings of the National Academy of Sciences*, **122**: e2406356121. doi:10.1073/pnas.2406356121.

Rathnaweera TD, Ranjith PG, Perera MSA, Haque A. 2016. Influence of CO_2–Brine Co-injection on CO_2 Storage Capacity Enhancement in Deep Saline Aquifers: An Experimental Study on Hawkesbury Sandstone Formation. *Energy & Fuels*, **30**: 4229–4243. doi:10.1021/acs.energyfuels.6b00113.

Rao ZH, Deng CH, Ma QY, et al. 2023. Effects of different crystal-inducing materials on crack self-healing process of cement stone under CCUS well conditions. *Drilling Fluid & Completion Fluid*, **40**: 495–501. doi:10.12358/j.issn.1001-5620.2023.04.012.

Rene N N, Liang WG, Chen YD, et al. 2025. Modeling of multiphase fluids flow in anisotropic rock mass during CO_2 sequestration in fractured reservoirs. *Geothermics*. **251**: 213904. doi:10.1016/j.geoen.2025.213904.

Rezk MG, Ibrahim AF. 2026. Impact of uncertainty in Utsira formation temperature and salinity on CO_2 storage: A field-scale reactive transport simulation study. *Carbon Capture Science & Technology*. **18**: 100567. doi:10.1016/j.ccst.2025.100567.

Sang SX, Liu SQ, Zhu QL, et al. 2023. Research progress on technical basis of CO_2 geological sequestration potential and energy resource synergy. *Journal of China Coal Society*, **48**: 2700–2716. doi:10.13225/j.cnki.jccs.cn23.0316.

Ting WW, Effendi SSW, Hu RE, et al. 2023. Directed evolution of Mesorhizobium loti carbonic anhydrase for carbon dioxide sequestration by MutaT7 and rational codon design. *Journal of the Taiwan Institute of Chemical Engineers*, **150**: 105065. doi:10.1016/j.jtice.2023.105065.

Tang WK, Li WQ, Lin ZT, et al. 2025. Geophysical monitoring technology and simulation in CO_2 geological storage: A comprehensive review. *Journal of Geochemical Exploration*, **143**: 205725. doi:10.1016/j.jgsce.2025.205725.

Wang M, Zhao WM, Li XS, et al. 2026. Comparative study on corrosion behavior of pack and hot-dip aluminized steels in high-temperature H_2–H_2S–CO_2–H_2O environments: insights into layer structure and degradation mechanisms[J]. *Materials Chemistry and Physics*, **349**(1): 131754. doi:10.1016/j.matchemphys.2025.131754.

Wang Y, Yue WT, Zhao YX, et al. 2021. Relationship between apparent permeability of shale gas, multiple flow mechanisms and effective stress evolution. *Science Technology and Engineering*, **21**: 4911–4917. doi:10.3969/j.issn.1671-1815.2021.12.023.

Wu ZW, Zhong L, Cai X, et al. 2026. Division of CO_2 flooding and storage development stages and optimization of water-alternating-gas injection parameters: A case study of block F in oilfield S. *Journal of Petroleum Science and Engineering*. doi:10.1016/j.petgeoen.2026.214606.

Xie J, Zhang KN, Wang YS, et al. 2016. Evaluation of CO_2 geological storage effect in deep saline aquifers of Ordos Basin. *Rock and Soil Mechanics*, **37**: 166–174. doi:10.16285/j.rsm.2016.01.020.

Xu XX, Shi SK, Zhang YH, et al. 2026. Corrosion behavior and mechanisms of martensitic heat-resistant steel in high temperature H_2O-CO_2-H_2S-H_2 environments. *Rock and Soil Mechanics*, **264**: 113735. doi:10.1016/j.corsci.2026.113735.

Yan XH, He WJ, Liao SW, et al. 2025. Enhancing CO_2 oversaturation in the confined water enables superior gas selectivity of 2D membranes. *The Journal of Physical Chemistry Letters*, **16**: 766–773. doi:10.1021/acs.jpclett.4c03228.

Yanagisawa N, Masuda Y, Asanuma H, et al. 2025. Estimation of casing material corrosion rates for supercritical geothermal development. *Geothermics*, **96**: 102149. doi:10.1016/j.geothermics.2021.102149.

Yang XM, Xiao P, Sun CY, et al. 2024. Research progress on kinetic promoters for light hydrocarbon and carbon dioxide hydrate formation. *The Chinese Journal of Process Engineering*, **24**: 1137–1148. doi:10.12034/j.issn.1009-606X.223332.

Zhang FJ, Juhlin C, Niemi A, et al. 2016. A feasibility and efficiency study of seismic waveform inversion for time-lapse monitoring of onshore CO_2 geological storage sites using reflection seismic acquisition geometries. *Interna-*

tional Journal of Greenhouse Gas Control, **48**: 134–141. doi:10.1016/j.ijggc.2015.11.015.

Zhang Q, Lin J, Zhe YN, et al. 2022. Research progress on potential evaluation of carbon dioxide geological storage in China. *China Petroleum and Chemical Standard and Quality*, **42**: 144–146. doi:10.3969/j.issn.1673-4076.2022.11.051.

Zhu BR, Chen GM, Lin H, et al. 2016. Dynamic pushover analysis method of deep-water jacket platform. *Acta Petrolei Sinica*, **37**(12): 1550–1556. doi:10.7623/syxb201612011.

Zhu ZW, Kumar N, Premadasa UI, et al. 2025. Polymer layer-accelerated CO_2 absorption in aqueous amino acid solutions. *ACS Applied Polymer Materials*, **7**: 689–698. doi:10.1021/acsapm.4c02798.

Zou XY, Zhu YT, Lv J, et al. 2024. Toward estimating CO_2 solubility in pure water and brine using cascade forward neural network and generalized regression neural network: Application to CO_2 dissolution trapping in saline aquifers. *ACS Omega*, **9**: 4705–4720. doi:10.1021/acsomega.3c07962.