

Review article

CO₂ Storage in Abandoned Coal Mine Goafs: From Conventional Reservoirs to Special Underground Spaces

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Abstract:

Driven by China's carbon peaking and carbon neutrality targets, CO₂ geological storage has been recognized as an important pathway for achieving deep decarbonization. However, existing CO₂ geological storage theories have been mainly developed based on conventional geological reservoirs, including deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams. The assumption of a continuous medium adopted in these theories is difficult to apply to abandoned coal mine goafs that are strongly affected by mining-induced disturbance. During mining activities, surrounding rock masses undergo failure, fracture development, and stress redistribution. As a result, a heterogeneous underground space with continuously evolving structural and mechanical properties is formed. These complex characteristics make it difficult for conventional reservoir theories to accurately describe CO₂ migration, rock structure evolution, and the long-term stability of the storage system. It is proposed that CO₂ storage in abandoned coal mine goafs requires a transition from conventional reservoir theories toward a multiscale and multiphysics-coupled theoretical framework for disturbed underground spaces. In this study, the key scientific challenges associated with CO₂ storage in abandoned coal mine goafs are discussed from three perspectives: microscale pore structure evolution, mesoscale CO₂ migration and leakage range evolution controlled by damage evolution, and macroscale long-term storage stability under multiphysics coupling conditions. The proposed framework provides theoretical support for underground space utilization in abandoned mines and large-scale CO₂ storage.

1 Introduction

Driven by China's carbon peaking and carbon neutrality targets, achieving large-scale CO₂ emission reductions has become a major scientific challenge in the fields of energy and environmental engineering. CO₂ geological storage, as an

important pathway for achieving deep decarbonization (IPCC, 2022; Zhang et al., 2025), has received extensive attention in recent years. Existing studies have demonstrated that CO₂ storage theories developed based on conventional geological reservoirs,

including deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams, have established relatively mature theoretical frameworks focusing on multiphase migration, storage mechanisms, and reservoir integrity evaluation (Bachu, 2000; Ren et al., 2025). However, with the increasing demand for large-scale CO₂ storage, limitations associated with conventional reservoir availability and regional applicability have gradually emerged. As a large-scale underground space generated during coal mining, abandoned coal mine goafs have advantages such as large available underground space, wide distribution, and potential compatibility with the green transformation of mining areas. Therefore, abandoned coal mine goafs provide a potential pathway for underground space utilization and CO₂ storage (Zhou et al., 2025; Menéndez et al., 2019).

Unlike the natural reservoir environments commonly used for conventional CO₂ storage, abandoned coal mine goafs represent typical disturbed underground spaces caused by engineering activities. During coal mining, rock masses undergo failure, fracture development, and stress redistribution. As a result, heterogeneous underground spaces with complex structures and continuously evolving characteristics are formed within goafs and overlying strata (Ren et al., 2024). Meanwhile, with the development of green mining technologies, the demand for underground space utilization and low-carbon transformation of coal mines has increased, providing new application scenarios for CO₂ storage in abandoned coal mine goafs (Zhang et al., 2017). Therefore, conventional reservoir theories based on the assumption of a continuous medium cannot accurately describe CO₂ migration behavior, rock structure evolution, and long-term changes in storage system stability within abandoned coal mine goafs. On the one hand, complex fracture networks and discontinuous structures in goafs govern CO₂ migration patterns, making conventional equivalent parameter models insufficient for representing actual migration processes. On the other hand, long-term water–rock–CO₂ interactions involving supercritical CO₂, formation water, and rock minerals may induce changes in pore structures and mechanical properties (Yin et al., 2025), thereby affecting storage stability. Furthermore, the overlying strata above goafs should not be considered as fixed storage boundaries. Instead, they represent complex structures that continuously evolve under the combined effects of mining-induced disturbance, stress adjustment, and CO₂ interactions. The fundamental differences between abandoned coal mine goafs and conventional reservoirs in terms of underground structural characteristics and storage conditions are illustrated in Fig.1.

Therefore, it is proposed that CO₂ storage in abandoned coal mine goafs requires a transition from conventional reservoir theories toward a theoretical framework for disturbed underground spaces. Based on this perspective, this study focuses on three key aspects: CO₂ migration mechanisms governed by complex pore structures, pore structure evolution and damage mechanisms induced by CO₂ interactions, and long-term stability evaluation of reservoir–caprock systems in abandoned coal mine goafs. This work provides a theoretical basis for underground space utilization in abandoned mines and large-scale CO₂ storage.

2 Applicability Challenges of Conventional CO₂ Geological Storage Theories in Abandoned Coal Mine Goafs

Conventional CO₂ geological storage theories have been mainly established based on the assumptions of continuous pore structures, stable permeability characteristics, and long-term integrity of storage boundaries. These theories have primarily focused on natural geological reservoirs, including deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams. However, abandoned coal mine goafs are complex underground spaces formed during coal mining, where internal structures and mechanical states are significantly affected by mining-induced disturbance. Therefore, conventional reservoir theories are insufficient for directly describing CO₂ migration processes, rock structure evolution, and long-term storage stability in abandoned coal mine goafs.

As illustrated in Fig.2, conventional CO₂ storage theories are generally based on several fundamental assumptions, including homogeneous continuous media, fixed permeability parameters, and stable reservoir–caprock systems. In contrast, abandoned coal mine goafs are strongly affected by mining-induced disturbance and exhibit discontinuous structures, dynamically evolving permeability characteristics, and continuously changing reservoir–caprock systems. Therefore, the applicability of conventional reservoir theories under abandoned coal mine goaf conditions is limited.

During coal mining, surrounding rock masses undergo unloading failure, roof movement, fracture development, and stress redistribution, resulting in heterogeneous underground spaces containing broken rock masses, complex fracture networks, and local void structures. Fluid migration pathways and mechanical responses within goafs are jointly controlled by fracture connectivity, structural distribution, and stress conditions. Conventional equivalent parameter models based on homogeneous continuous media are therefore insufficient for accurately describing these evolving characteristics. Consequently, CO₂ storage in abandoned coal mine goafs does not simply involve expanding underground storage space, but requires the development of theoretical approaches suitable for complex underground spaces. Three key scientific challenges should be addressed: complex structural characterization, CO₂–rock interactions, and long-term stability evaluation of reservoir–caprock systems.

2.1 Challenges Posed by Complex Structures of Abandoned Coal Mine Goafs to Conventional Reservoir Assumptions

Currently, some studies on CO₂ storage in abandoned coal mine goafs still adopt conventional porous media theories and describe fluid migration processes using equivalent porosity and permeability parameters. Although such approaches can reduce model complexity, they cannot sufficiently represent the controlling effects of mining-induced complex fracture structures on CO₂ migration behavior. Unlike natural sedimentary reservoirs, the internal structures of abandoned coal mine goafs exhibit significant discontinuity. Coal mining induces roof failure, strata movement, and fracture network development. The

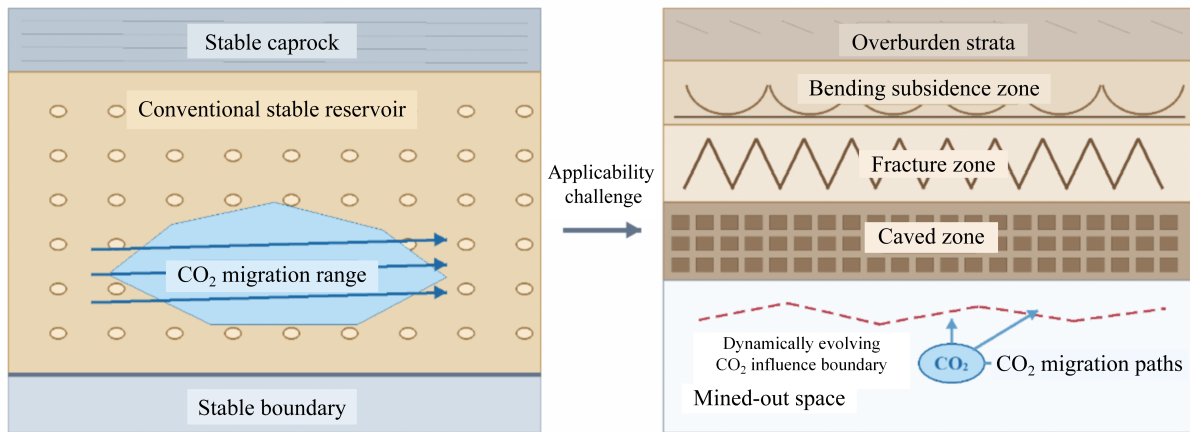


Fig. 1 Schematic comparison of CO₂ storage environments between conventional reservoirs and abandoned coal mine goafs

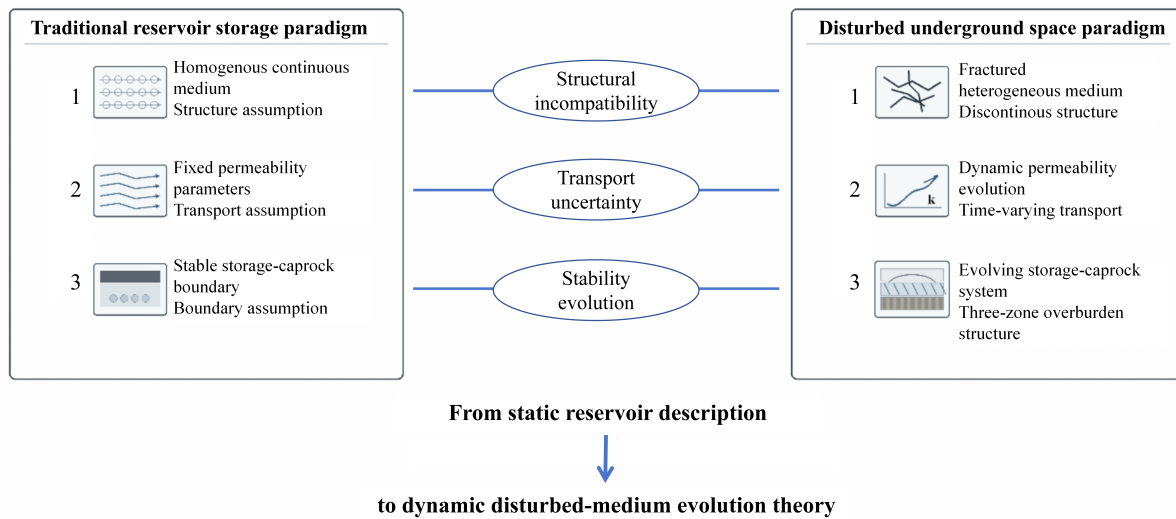


Fig. 2 Comparison between conventional CO₂ storage assumptions and response characteristics of abandoned coal mine goafs under complex underground conditions

connectivity between fractures at different scales, preferential flow pathways, and distribution of broken rock masses jointly control CO₂ migration pathways and spatial distribution. Therefore, the use of fixed equivalent parameters to describe goaf structures cannot accurately capture the influence of complex fracture systems on CO₂ migration processes.

Meanwhile, permeability characteristics in abandoned coal mine goafs are also affected by stress redistribution, groundwater interactions, and long-term CO₂ exposure, exhibiting significant dynamic evolution. Future studies should move beyond the assumption of homogeneous continuous media by incorporating complex structural characteristics, pore-fracture evolution mechanisms, and permeability evolution into an integrated characterization framework. Multiscale description methods should be developed to accurately represent the actual structural features of abandoned coal mine goafs.

2.2 Challenges of CO₂–Rock Interactions and Pore Structure Damage Mechanisms

Conventional CO₂ storage studies have mainly focused on fluid migration, trapping, and fixation processes, while the structural changes of rocks induced by long-term CO₂ exposure have received relatively limited attention. However, continuous water–rock–CO₂ interactions occur among CO₂, formation water, and rock minerals, including mineral dissolution, element migration, secondary mineral precipitation, and pore structure evolution (Xu et al., 2004; Gaus, 2010). For abandoned coal mine goafs that have already experienced mining-induced disturbance, CO₂ interactions may further alter existing fracture structures and rock integrity. Since overlying strata contain numerous initial fractures and localized damaged zones, CO₂ injection may modify pore structures, fracture connectivity, and permeability characteristics through water–rock–CO₂ interactions, thereby affecting storage system stability (Ogata et al., 2020; Chen et al., 2025).

Therefore, CO₂ storage in abandoned coal mine goafs is not merely a fluid migration process, but a complex process involving interactions among CO₂ migration, pore structure evolution, and mechanical responses of rock masses. Future research should shift from conventional fluid migration models toward coupled models incorporating CO₂–rock interactions and damage evolution. The relationship between microscale pore structure damage and mesoscale mechanical responses should be established. Pore structure changes, damage evolution, permeability variation, and deterioration of rock mechanical properties should be integrated into a unified analytical framework to elucidate the cross-scale transfer mechanism from microscale rock damage induced by CO₂ interactions to mesoscale mechanical responses, macroscale structural weakening, and changes in storage stability.

2.3 Challenges in Long-Term Stability Evaluation of Reservoir–Caprock Systems in Abandoned Coal Mine Goafs

In conventional CO₂ storage systems, caprock integrity is considered a key factor ensuring long-term storage safety (Chen et al., 2024). Related studies have mainly focused on caprock permeability, breakthrough pressure, and fault stability. However, these studies are generally established based on relatively stable reservoir structures. In contrast, the overlying strata above abandoned coal mine goafs develop distinct structural zones under mining activities, including caved zones, fractured zones, and bending subsidence zones. Different zones exhibit significant differences in fracture development, permeability characteristics, and mechanical stability. Moreover, their structural states continue to be affected by stress redistribution, groundwater interactions, and long-term CO₂ exposure.

During long-term CO₂ injection, variations in pore pressure and water–rock–CO₂ interactions may further influence fracture development and rock integrity, causing reservoir–caprock systems in abandoned coal mine goafs to exhibit continuous long-term evolution characteristics. Overall, safety evaluation of CO₂ storage in abandoned coal mine goafs cannot rely solely on fixed reservoir parameters and initial sealing conditions. Instead, comprehensive evaluation methods considering reservoir–caprock evolution, multiphysics coupling effects, and long-term stability changes should be developed. Research emphasis should be extended from evaluating storage capacity and initial sealing performance to assessing the long-term safety of storage systems under CO₂ exposure.

3 Multiscale Key Scientific Issues in CO₂ Storage in Abandoned Coal Mine Goafs

CO₂ geological storage in abandoned coal mine goafs is not merely a process of CO₂ injection and storage. The key scientific challenge lies in the complex coupling among CO₂ migration, rock structure evolution, and storage system stability under mining-induced disturbance conditions. Unlike conventional natural reservoirs, CO₂ storage in abandoned coal mine goafs exhibits significant multiscale characteristics, requiring a systematic understanding of storage mechanisms from a multiscale perspective. Specifically, at the microscale, CO₂ interactions

induce pore structure changes and additional damage in rocks, thereby modifying fluid storage spaces and migration pathways. These microscale damage processes are further propagated to the mesoscale, resulting in deterioration of mechanical properties, fracture development, and changes in permeability characteristics, which subsequently control CO₂ migration range. At the macroscale, multiphysics coupling processes determine the long-term stability of storage systems. Therefore, establishing the scale-transfer relationship from microscale damage to mesoscale mechanical responses and macroscale stability evolution is critical for achieving safe CO₂ storage in abandoned coal mine goafs.

To further reveal the cross-scale relationships and parameter transfer mechanisms among microscale damage evolution, mesoscale structural responses, and macroscale storage stability during CO₂ storage in abandoned coal mine goafs, a multiscale coupled evolution and feedback mechanism is established in this study, as illustrated in Fig.3.

3.1 Microscale: CO₂ Migration and Rock Damage Mechanisms Controlled by Complex Pore Structures

Conventional reservoir studies generally assume that pore structures remain relatively stable. However, overlying strata in abandoned coal mine goafs experience mining-induced disturbance, resulting in the formation of multiscale pore structures and microfractures. Consequently, the initial migration behavior of CO₂ is strongly controlled by pore structure characteristics. Rock pore structures not only determine the initial migration pathways of CO₂ but also provide important reaction sites for water–rock–CO₂ interactions. Pore size distribution, pore connectivity, and fracture network structures jointly influence CO₂ diffusion, retention, and subsequent reaction processes. Under supercritical CO₂ conditions, the strong dissolution capacity and chemical reactivity of the fluid may further modify rock pore structures, resulting in changes in permeability characteristics and mechanical properties. Therefore, CO₂ storage in abandoned coal mine goafs requires an understanding of the intrinsic relationship between CO₂-induced pore structure evolution and fluid migration behavior. Conventional methods based on average porosity and permeability parameters are insufficient for accurately describing rock property variations under complex structural conditions. More refined approaches capable of characterizing pore-fracture evolution processes should be developed.

In recent years, micro-computed tomography (micro-CT) scanning and digital rock technologies have provided new approaches for characterizing complex pore structures (Nabipour et al., 2024). By analyzing structural changes before and after CO₂ interactions, pore connectivity, fracture evolution, and structural damage characteristics can be obtained. Meanwhile, relationships between microscale structural parameters and macroscale flow behaviors can be established. Future studies should combine in situ micro-CT experiments, digital rock analysis, and rock mechanical tests to elucidate the mechanisms of pore structure evolution and mechanical property changes induced by CO₂ interactions. These studies can provide fun-

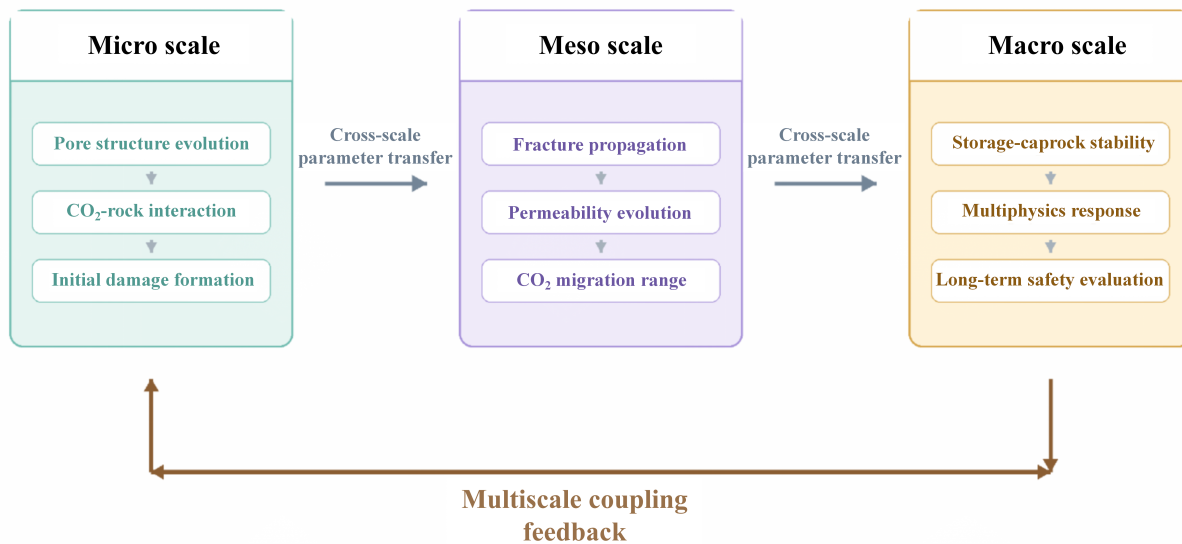


Fig. 3 Multiscale evolution and feedback mechanism of CO₂ storage in abandoned coal mine goafs from microscale damage to macroscale stability

damental support for CO₂ migration modeling and multiscale theoretical development in abandoned coal mine goafs.

3.2 Mesoscale: Evolution Mechanism of CO₂ Leakage Range Controlled by Damage Evolution

Microscale pore structures determine the initial migration characteristics of CO₂, while mesoscale damage evolution further affects long-term CO₂ migration by modifying fracture structures, permeability characteristics, and flow pathways. Conventional CO₂ storage models generally regard permeability as an intrinsic reservoir parameter. However, permeability in abandoned coal mine goafs dynamically evolves due to mining-induced disturbance, stress redistribution, fracture development, and CO₂ interactions. The fractures within overlying strata are not static structures but continuously adjust under the combined effects of stress variation, fluid interactions, and water-rock-CO₂ interactions. After entering the rock mass, CO₂ mainly migrates along existing fractures and preferential pathways, while migration pathways continuously evolve with structural changes. Therefore, CO₂ migration behavior is controlled not only by initial permeability conditions but also by fracture evolution and permeability variations.

Consequently, CO₂ storage in abandoned coal mine goafs requires a transition beyond conventional fixed-parameter models. CO₂ migration and leakage range prediction models considering mining effects and damage evolution should be developed. By introducing damage variables into flow governing equations, the transition from fixed permeability descriptions to damage-dependent dynamic permeability characterization can be achieved. Combined with pore structure evolution obtained at the microscale, scale-transfer relationships between microscale parameters and mesoscale models can be established. Through quantitative relationships between damage variables and permeability evolution, CO₂ migration range prediction and leakage risk assessment can be achieved,

providing theoretical support for storage zone delineation and engineering safety design.

3.3 Macroscale: Long-Term Stability Evaluation of Storage Systems under Multiphysics Coupling Conditions

At the engineering scale, CO₂ storage in abandoned coal mine goafs represents a typical multiphysics coupling problem. CO₂ injection not only changes underground pressure distributions but also affects stress states, deformation behaviors of rock masses, and water-rock-CO₂ interaction processes. Therefore, single-physics flow models are insufficient for accurately describing long-term storage responses. Conventional CO₂ storage safety evaluations mainly focus on reservoir pressure variations and caprock integrity. However, storage in abandoned coal mine goafs additionally requires consideration of mining-induced changes in rock mechanical properties. Since reservoir-caprock systems in goafs exhibit significant spatial heterogeneity and dynamic evolution characteristics, pore pressure changes caused by CO₂ injection may further influence stress distribution, fracture development, and rock deformation, thereby affecting long-term storage stability. Therefore, multiphysics coupling models incorporating CO₂ migration, pore pressure evolution, rock deformation, and damage evolution should be developed. By coupling porous media flow, CO₂ transport, and poroelasticity models (Biot, 1956; Wang et al., 2024), interactions among pressure fields, concentration fields, and stress fields can be described. Meanwhile, damage evolution models should be incorporated to improve long-term stability prediction capability.

Future research on CO₂ storage in abandoned coal mine goafs should move from single CO₂ migration simulations toward integrated analyses of the entire "injection-storage-monitoring" process. By developing integrated models that consider goaf formation, CO₂ injection, and long-term stability evaluation, dynamic prediction of storage safety can be achieved. Overall,

CO₂ storage in abandoned coal mine goafs exhibits significant multiscale characteristics. At the microscale, pore structure evolution and damage mechanisms induced by CO₂ interactions should be revealed. At the mesoscale, CO₂ migration and leakage range prediction models considering damage evolution should be established. At the macroscale, long-term stability evaluation methods for reservoir–caprock systems under multiphysics coupling conditions should be developed. These three scales are integrated through parameter transfer and feedback mechanisms, promoting the transition of CO₂ storage theories from conventional reservoir parameter descriptions toward pore–fracture structure evolution and multiphysics coupling mechanisms.

4 Future Directions: Development of a Theoretical Framework for CO₂ Storage in Disturbed Underground Spaces

The development of CO₂ geological storage in abandoned coal mine goafs essentially represents an extension of conventional CO₂ storage theories to disturbed underground spaces. Due to the characteristics of mining-induced disturbance, structural heterogeneity, and long-term evolution of reservoir–caprock systems, conventional reservoir evaluation methods cannot fully satisfy the requirements of long-term CO₂ storage. Therefore, a multiscale and multiphysics-coupled theoretical framework suitable for complex structural conditions of abandoned coal mine goafs should be developed to link microscopic mechanisms with engineering applications.

With the development of high-resolution experimental characterization, multiscale numerical simulations, and intelligent computing technologies, future research on CO₂ storage in abandoned coal mine goafs should mainly focus on three aspects: multiscale structural characterization, multiphysics coupling simulation, and intelligent safety evaluation.

4.1 Multiscale In Situ Experimental System and Dynamic Evolution Mechanisms of Pore Structures

The development of CO₂ storage theories for abandoned coal mine goafs relies on an accurate understanding of pore–fracture structures under mining-induced disturbance conditions. Conventional reservoir studies mainly depend on macroscopic parameter analysis. However, complex pore structures, fracture networks, and broken rock zones exist within abandoned coal mine goafs, and their actual evolution characteristics cannot be fully revealed using traditional testing methods. In recent years, experimental characterization techniques have gradually developed from conventional static measurements toward integrated in situ dynamic characterization based on multiple technologies. Therefore, a comprehensive experimental system integrating experimental specimens, in situ dynamic observation, digital rock reconstruction, and cross-scale parameter transfer should be established. Such a system can link microscopic structural evolution with macroscopic storage evaluation, as illustrated in Fig.4.

For CO₂ storage in abandoned coal mine goafs, conventional micro-CT scanning alone is insufficient to characterize the

multiscale evolution of complex underground spaces. Therefore, future studies should establish an integrated experimental system based on 4D in situ micro-CT scanning, combined with digital rock reconstruction, rock mechanical testing, and water–rock–CO₂ interaction experiments. This system can enable simultaneous observation and quantitative analysis of pore structure evolution, fracture development, permeability variation, and mechanical property changes during CO₂ injection. Furthermore, 3D-printed porous media models and microfluidic experimental platforms can be incorporated to construct visualization-based experimental systems with controllable pore structures and fracture networks. These systems can provide real-time observations of CO₂ migration, pore structure evolution, and fluid–rock interaction processes. By integrating multiscale experimental data with digital rock models, scale-transfer relationships from microscopic pore structure parameters to mesoscale migration models and macroscopic engineering evaluation models can be established. These developments will provide an experimental basis for developing a multiscale theoretical framework for CO₂ storage in abandoned coal mine goafs.

4.2 Dynamic Stability Evaluation Methods Considering Reservoir–Caprock Evolution

Existing CO₂ storage numerical models are generally established based on relatively stable reservoir parameters and boundary conditions. Multiphysics coupling methods are commonly used to predict pressure variations and structural responses during CO₂ injection. However, abandoned coal mine goafs differ from natural stable reservoirs. Their reservoir–caprock systems continue to evolve after mining-induced disturbance. Pore structures, fracture networks, and permeability characteristics exhibit significant temporal evolution. Therefore, CO₂ storage models for abandoned coal mine goafs should move beyond the assumptions of fixed parameters and static boundaries. New evaluation frameworks capable of describing dynamic evolution of reservoir–caprock systems should be developed.

The key challenge in model development is not simply to introduce more coupled equations, but to dynamically update model parameters and boundary conditions. Pore structure changes, rock damage evolution, and permeability variations should be treated as dynamic state variables rather than fixed input parameters in conventional models. Based on bidirectional feedback between experimental observations and numerical simulations, dynamically updated models should be developed. By integrating pore structure evolution parameters obtained at the microscale, damage evolution mechanisms at the mesoscale, and reservoir–caprock responses at the macroscale, dynamic updates and long-term prediction of storage system states can be achieved. Meanwhile, digital evaluation methods covering the entire “injection–storage–monitoring” process should be developed. Field monitoring data, experimental results, and multiphysics models should be integrated to establish a new safety evaluation framework combining mechanism-based models and data-driven approaches. Such developments will provide theoretical support for predicting long-term stabil-

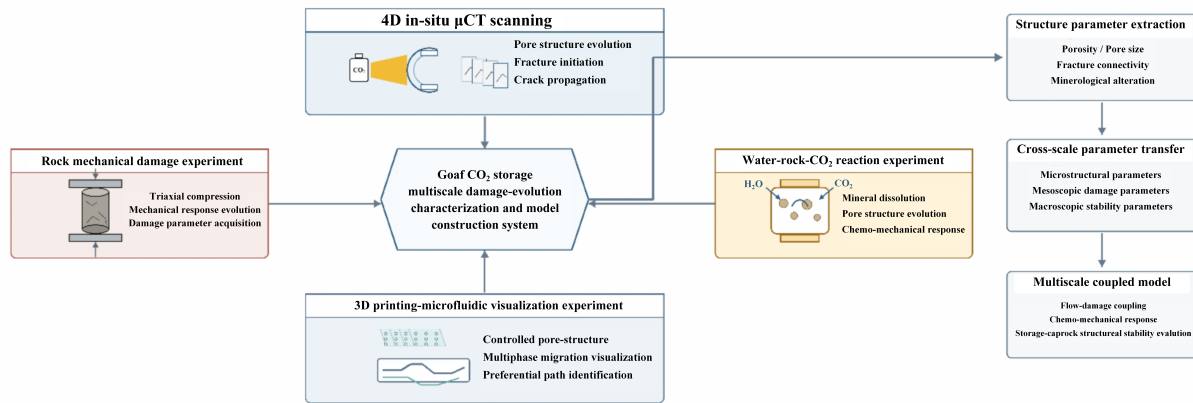


Fig. 4 Multiscale damage evolution characterization and coupled modeling framework for CO₂ storage in abandoned coal mine goafs

ity of CO₂ storage in abandoned coal mine goafs.

4.3 Safety Evaluation System Driven by Digital Monitoring and Intelligent Prediction

With the continuous expansion of underground space utilization, conventional numerical simulation methods face limitations in long-term and large-scale prediction. In recent years, the development of artificial intelligence, big data analysis, and digital technologies has provided new approaches for system monitoring, dynamic modeling, and safety evaluation of complex underground systems (Aljehani, 2025; Wan et al., 2026; Gong et al., 2024). For CO₂ storage in abandoned coal mine goafs, future studies should integrate experimental data, numerical simulation results, and field monitoring information to establish a digital monitoring and intelligent evaluation system for long-term operation. Such a system can enable dynamic prediction of CO₂ migration ranges, pressure variations, and potential risks. Under conditions of complex structures and high parameter uncertainty in abandoned coal mine goafs, data-driven methods can assist in identifying nonlinear relationships and improving the prediction of storage system states. It should be emphasized that intelligent methods cannot replace geomechanical mechanism analysis. Instead, they should be established based on reliable experimental understanding and physical models.

An integrated research framework combining “mechanism-based models–experimental data–intelligent evaluation” should be established by integrating experimental characterization, multiscale simulation, and intelligent prediction. This approach will promote the transformation of abandoned coal mine underground spaces from traditional resource extraction spaces toward safe, efficient, and intelligent low-carbon energy utilization spaces.

5 Conclusions

CO₂ geological storage in abandoned coal mine goafs provides a new pathway for underground space utilization to support the green transformation of exhausted mining areas and carbon emission reduction. However, abandoned coal mine goafs are fundamentally different from conventional stable

reservoirs. Their internal structures, flow conditions, and mechanical states are affected by mining-induced disturbance and continuously evolve. Therefore, CO₂ storage theories established based on stable reservoir assumptions cannot be directly applied.

This study proposes that CO₂ storage in abandoned coal mine goafs requires a transition from conventional stable reservoir theories toward a multiscale and multiphysics-coupled theoretical framework for disturbed underground spaces. Such a framework should reveal pore structure evolution and damage mechanisms induced by CO₂ interactions, and establish scale-transfer relationships from microscale structural damage to mesoscale mechanical responses and macroscale reservoir–caprock stability evolution. Meanwhile, models should move beyond the assumptions of fixed parameters and static boundaries. Pore structure changes, damage evolution, and permeability variations should be incorporated as dynamic state variables into CO₂ migration and leakage range prediction models. Multiphysics coupling methods considering long-term evolution of reservoir–caprock systems should also be developed. The fundamental transition lies in replacing storage evaluation methods based on fixed reservoir parameters with a new evaluation framework for disturbed underground spaces that considers pore–fracture structure evolution, damage accumulation, and dynamic adjustment of reservoir–caprock systems.

In the future, through the combined development of multiscale in situ experimental characterization, digital rock analysis, dynamic multiphysics simulation, and intelligent prediction methods, the characterization of structural evolution and the safety evaluation of CO₂ storage in abandoned coal mine goafs can be further improved. These developments will promote the transformation of abandoned coal mine underground spaces from traditional mining spaces toward low-carbon energy utilization spaces, providing theoretical support for large-scale CO₂ storage and green transformation of mining areas.

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Conflict of interest

The authors declare no competing interest.

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