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CO_2 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, CO_2 geological storage has been recognized as an important pathway for achieving deep decarbonization. However, existing CO_2 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 render conventional reservoir theories insufficient to accurately characterize CO_2 migration patterns, rock structure evolution processes, and the long-term stability of storage systems. It is proposed that CO_2 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 CO_2 storage in abandoned coal mine goafs are discussed from three perspectives: microscale pore structure evolution, mesoscale CO_2 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 CO_2 storage.

1 Introduction

Driven by China's carbon peaking and carbon neutrality targets, achieving large-scale CO_2 emission reductions has become a major scientific challenge in the fields of energy and environmental engineering. CO_2 geological storage, as an important pathway for achieving deep decarbonization (IPCC, 2022; Zhang et al., 2025), has received extensive attention in re-

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cent years. Existing studies have demonstrated that CO_2 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). However, with the increasing demand for large-scale CO_2 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 CO_2 storage (Zhou et al., 2025; Menéndez et al., 2019).

In recent years, research on CO_2 storage in abandoned coal mine goafs has gradually progressed from conceptual feasibility assessment toward quantitative investigations of gas migration, storage performance, geochemical reactions, and multiphysics coupling. Teng et al. developed a fully coupled hydromechanical model incorporating CO_2 adsorption, coal softening, and non-Darcy flow to evaluate the feasibility and controlling mechanisms of CO_2 storage in abandoned coal mines (Teng et al., 2024). Zhou et al. combined CO_2 adsorption experiments with numerical simulations to investigate CO_2 diffusion and migration in abandoned coal mine goafs, demonstrating that the injection-well location and residual-coal thickness significantly influence CO_2 migration pathways and storage performance (Zhou et al., 2025). More recently, Dai et al. integrated mining-induced overburden fracture evolution with TOUGHREACT simulations to investigate pressure evolution, multiphase CO_2 migration, and mineral dissolution–precipitation reactions in coal mine goafs, and further compared the storage behavior of fractured goafs with that of continuous geological bodies (Dai et al., 2026). Related studies have also extended CO_2 storage research from abandoned coal mine goafs to other mined-out spaces. Qiao et al. systematically investigated CO_2 sequestration methods and their feasibility in abandoned metal mine goafs, further demonstrating the potential of mining-disturbed underground spaces for geological CO_2 storage (Qiao et al., 2026).

Although these studies differ in their research objects and methodological focuses, they collectively demonstrate a progressive development from storage-feasibility assessment toward quantitative characterization of CO_2 migration, physicochemical interactions, and storage stability in mining-disturbed underground spaces. Nevertheless, compared with laboratory experiments and numerical simulations, field-scale CO_2 injection, monitoring, and long-term verification specifically targeting abandoned coal mine goafs remain limited, mainly due to the complexity of goaf structures, difficulties in site characterization, and challenges in establishing reliable monitoring systems. Existing studies have provided important foundations for understanding individual processes; however, most investigations remain focused on specific mechanisms or individual spatial scales. The cross-scale relationships among mining-induced pore-fracture structures, CO_2–rock interactions, damage-dependent permeability evolution, and long-term reservoir–caprock stability remain insufficiently understood. In particular, a unified theoretical framework capable of linking microscale structural evolution, mesoscale migration and damage processes, and macroscale long-term storage stability has not yet been established for abandoned coal mine goafs. Therefore, further development of a multiscale and multiphysics-coupled framework is required to systematically describe the dynamic evolution of CO_2 storage in such disturbed underground spaces.

Unlike the natural reservoir environments commonly used for conventional CO_2 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 CO_2 storage in abandoned coal mine goafs (Zhang et al., 2017). Therefore, conventional reservoir theories based on the assumption of a continuous medium are insufficient to accurately characterize CO_2 migration patterns, rock structure evolution processes, 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 CO_2 migration patterns, making conventional equivalent parameter models insufficient for representing actual migration processes. On the other hand, long-term water–rock–CO_2 interactions involving supercritical CO_2, formation water, and rock minerals may induce changes in pore structures and mechanical properties, 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 CO_2 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 CO_2 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: CO_2 migration mechanisms governed by complex pore structures, pore structure evolution and damage mechanisms induced by CO_2 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 CO_2 storage.

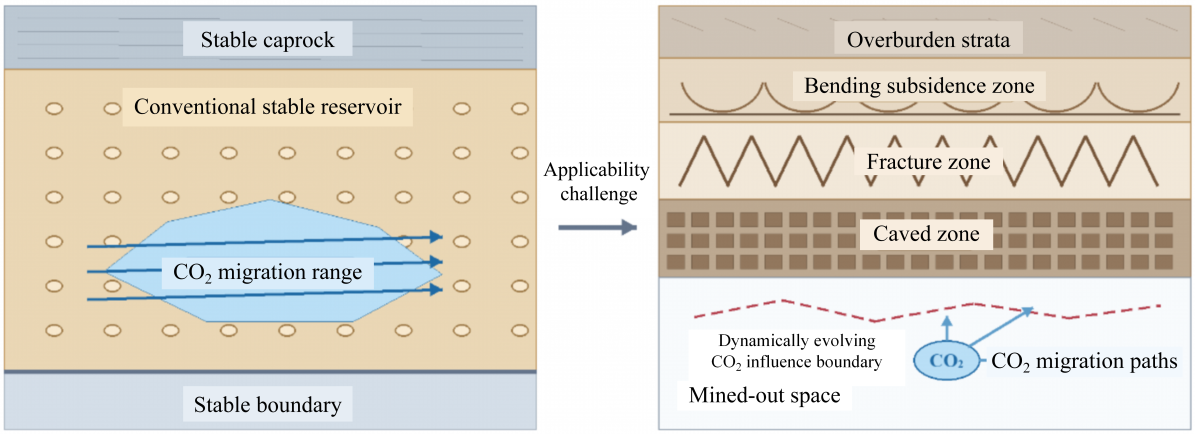

Fig. 1 Schematic comparison of CO_2 storage environments between conventional reservoirs and abandoned coal mine goafs

2 Applicability Challenges of Conventional CO_2 Geological Storage Theories in Abandoned Coal Mine Goafs

Conventional CO_2 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 CO_2 migration processes, rock structure evolution, and long-term storage stability in abandoned coal mine goafs.

As illustrated in Fig.2, conventional CO_2 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, CO_2 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, CO_2–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 CO_2 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 may not adequately capture the controlling effects of complex mining-induced fracture structures on CO_2 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 connectivity between fractures at different scales, preferential flow pathways, and distribution of broken rock masses jointly control CO_2 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 CO_2 migration processes.

Meanwhile, permeability characteristics in abandoned coal mine goafs are also affected by stress redistribution, groundwater interactions, and long-term CO_2 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 CO_2–Rock Interactions and Pore Structure Damage Mechanisms

Conventional CO_2 storage studies have mainly focused on fluid migration, trapping, and fixation processes, while the structural changes of rocks induced by long-term CO_2 exposure

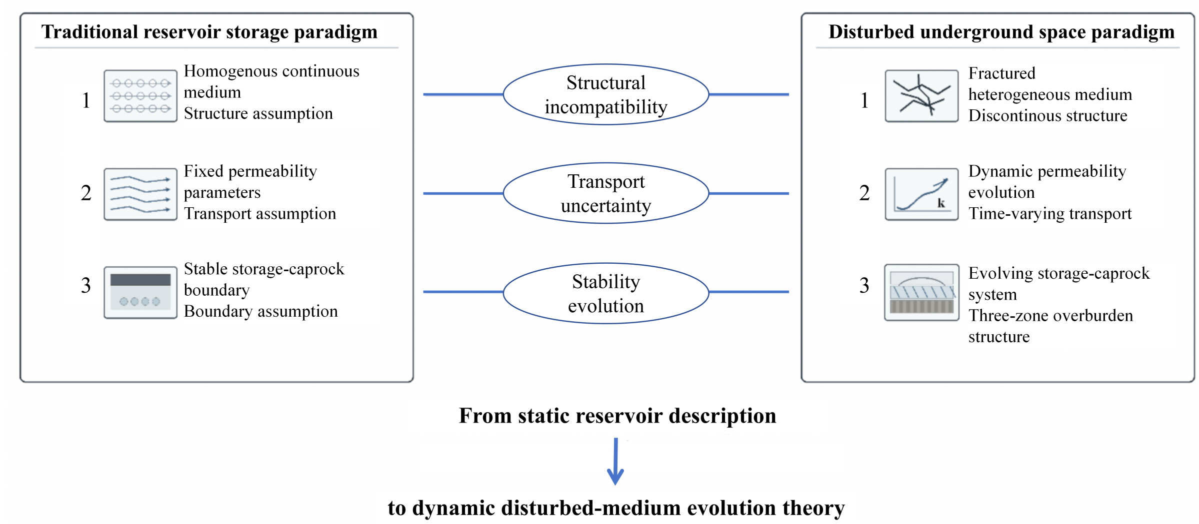

Fig. 2 Comparison between conventional CO_2 storage assumptions and response characteristics of abandoned coal mine goafs under complex underground conditions

have received relatively limited attention. However, continuous water–rock–CO_2 interactions occur among CO_2, 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, CO_2 interactions may further alter existing fracture structures and rock integrity. Since overlying strata contain numerous initial fractures and localized damaged zones, CO_2 injection may modify pore structures, fracture connectivity, and permeability characteristics through water–rock–CO_2 interactions, thereby affecting storage system stability (Ogata et al., 2020; Chen et al., 2025).

Therefore, CO_2 storage in abandoned coal mine goafs is not merely a fluid migration process, but a complex process involving interactions among CO_2 migration, pore structure evolution, and mechanical responses of rock masses. Future research should shift from conventional fluid migration models toward coupled models incorporating CO_2–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 CO_2 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 CO_2 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 CO_2 exposure.

During long-term CO_2 injection, variations in pore pressure and water–rock–CO_2 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 CO_2 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 CO_2 exposure.

3 Multiscale Key Scientific Issues in CO_2 Storage in Abandoned Coal Mine Goafs

CO_2 geological storage in abandoned coal mine goafs is not merely a process of CO_2 injection and storage. The key scientific challenge lies in the complex coupling among CO_2 migration, rock structure evolution, and storage system stability under mining-induced disturbance conditions. Unlike conventional natural reservoirs, CO_2 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, CO_2 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 CO_2 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 CO_2 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 CO_2 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: CO_2 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 CO_2 is strongly controlled by pore structure characteristics. Rock pore structures not only determine the initial migration pathways of CO_2 but also provide important reaction sites for water–rock–CO_2 interactions. Pore size distribution, pore connectivity, and fracture network structures jointly influence CO_2 diffusion, retention, and subsequent reaction processes. Under supercritical CO_2 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. Unlike conventional reservoir rocks with relatively intact and stable initial structures, rock masses in abandoned coal mine goafs have already experienced mining-induced unloading, fracture development, damage accumulation, and stress redistribution before CO_2 injection. Therefore, CO_2–rock interactions in goafs occur within a pre-damaged and strongly heterogeneous geological medium. Pre-existing mining-induced fractures can provide preferential pathways for CO_2 migration and increase the contact area between CO_2-bearing fluids and rock minerals. Meanwhile, mineral dissolution and precipitation induced by CO_2–water–rock reactions may further modify pore-fracture connectivity and local mechanical properties. These changes may interact with the existing mining-induced damage and stress state, resulting in a coupled evolution of chemical alteration, mechanical damage, and transport properties. Therefore, compared with conventional reservoir rocks, the key characteristic of CO_2–rock interactions in abandoned goafs lies in the superposition and feedback between mining-induced initial damage and subsequent CO_2-induced physicochemical alteration. This coupling should be explicitly considered when evaluating the long-term evolution of pore-fracture structures, permeability, and mechanical stability. Therefore, CO_2 storage in abandoned coal mine goafs requires an understanding of the intrinsic relationship between CO_2-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 CO_2 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 CO_2 interactions. These studies can provide fundamental support for CO_2 migration modeling and multiscale theoretical development in abandoned coal mine goafs.

3.2 Mesoscale: Evolution Mechanism of CO_2 Leakage Range Controlled by Damage Evolution

Microscale pore structures determine the initial migration characteristics of CO_2, while mesoscale damage evolution further affects long-term CO_2 migration by modifying fracture structures, permeability characteristics, and flow pathways. Conventional CO_2 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 CO_2 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–$CO_2$2 interactions (Yin et al., 2025). After entering the rock mass, CO_2 mainly migrates along existing fractures and preferential pathways, while migration pathways continuously evolve with structural changes. Therefore, CO_2 migration behavior is controlled not only by initial permeability conditions but also by fracture evolution and permeability variations.

Consequently, CO_2 storage in abandoned coal mine goafs requires a transition beyond conventional fixed-parameter models. CO_2 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, CO_2 migration range prediction and leakage risk assessment can be achieved, providing theoretical support for storage zone delineation and engineering safety design.

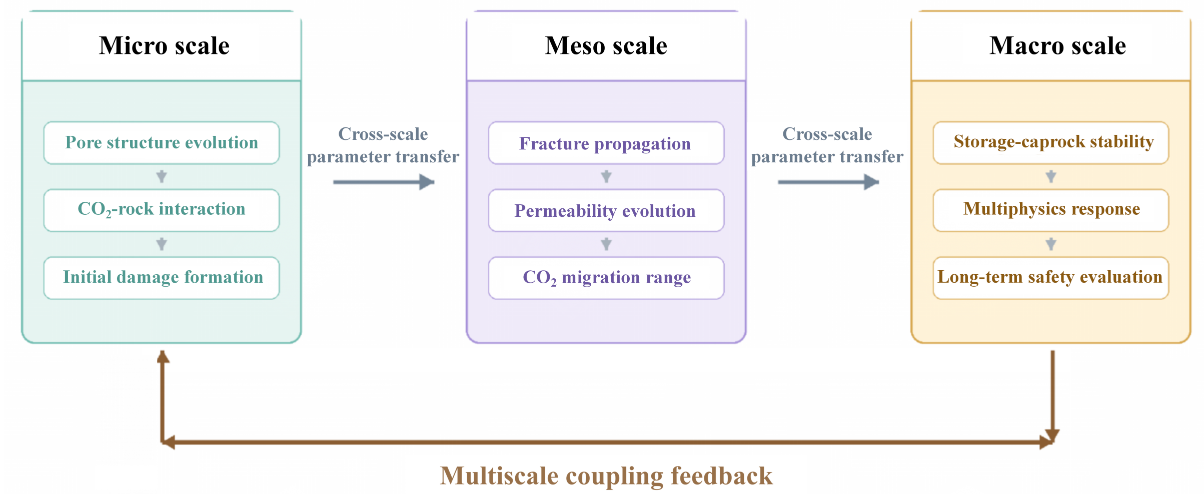

Fig. 3 Multiscale evolution and feedback mechanism of CO_2 storage in abandoned coal mine goafs from microscale damage to macroscale stability

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

At the engineering scale, CO_2 storage in abandoned coal mine goafs represents a typical multiphysics coupling problem. CO_2 injection not only changes underground pressure distributions but also affects stress states, deformation behaviors of rock masses, and water–rock–CO_2 interaction processes. Therefore, single-physics flow models are insufficient for accurately describing long-term storage responses. Conventional CO_2 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 CO_2 injection may further influence stress distribution, fracture development, and rock deformation, thereby affecting long-term storage stability. Therefore, multiphysics coupling models incorporating CO_2 migration, pore pressure evolution, rock deformation, and damage evolution should be developed. By coupling porous media flow, CO_2 transport, and poroelasticity models (Biot, 1956; Teng 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 CO_2 storage in abandoned coal mine goafs should move from single CO_2 migration simulations toward integrated analyses of the entire “injection–storage–monitoring” process. By developing integrated models that consider goaf formation, CO_2 injection, and long-term stability evaluation, dynamic prediction of storage safety can be achieved. Overall, CO_2 storage in abandoned coal mine goafs exhibits significant multiscale characteristics. At the microscale, pore structure evolution and damage mechanisms induced by CO_2 interactions should be revealed. At the mesoscale, CO_2 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. The linkage among micro-, meso-, and macroscales should be established through a hierarchical parameter-transfer and feedback framework rather than by simply combining models at different scales. At the microscale, pore-fracture structural parameters obtained from in situ micro-CT experiments and digital rock analysis, together with interfacial parameters characterized by complementary experiments, can be used to characterize changes in porosity, connectivity, tortuosity, and effective transport properties. These parameters can be upscaled to the mesoscale through equivalent characterization, representative elementary volume analysis, and experimentally calibrated constitutive relationships, providing inputs for fracture propagation, damage evolution, and permeability evolution models. The resulting mesoscale effective parameters and constitutive relationships can then be incorporated into macroscale multiphysics models to predict CO_2 migration and reservoir–caprock stability. Conversely, macroscale pressure, stress, and deformation responses can provide boundary conditions for mesoscale and microscale analyses, forming a feedback loop across different scales. Therefore, the micro–meso–macro framework should be regarded as a hierarchical and bidirectional coupling system involving parameter extraction, upscaling, model calibration, and feedback updating. Such a hierarchical cross-scale framework can promote the transition of CO_2 storage theories from conventional reservoir parameter descriptions toward dynamic descriptions of pore-fracture structure evolution and multiphysics coupling mechanisms.

4 Future Directions: Development of a Theoretical Framework for CO_2 Storage in Disturbed Underground Spaces

The development of CO_2 geological storage in abandoned coal mine goafs essentially represents an extension of conventional CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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–CO_2 interaction experiments. This system can enable simultaneous observation and quantitative analysis of pore structure evolution, fracture development, permeability variation, and mechanical property changes during CO_2 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 CO_2 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. Quantitative cross-scale parameter transfer can be progressively achieved through parameter extraction, equivalent parameter determination and model calibration. Pore-scale parameters, including structural parameters obtained from 4D in situ micro-CT and digital rock analysis (e.g., porosity, pore-size distribution, fracture connectivity, and tortuosity), together with interfacial parameters characterized by complementary experiments (e.g., contact angle and wettability), can be used to determine effective transport properties such as permeability, relative permeability, and capillary pressure. Pore-scale numerical simulations and representative elementary volume (REV) analysis can then be employed to obtain equivalent transport parameters for mesoscale models by evaluating these properties over progressively larger pore-fracture volumes until representative values are reached. These parameters can then be introduced into mesoscale flow–damage models. Experimentally calibrated relationships among damage, fracture evolution, porosity, and permeability can further provide effective parameters for macroscale CO_2 migration and reservoir–caprock stability models. However, a unified quantitative transfer relationship for abandoned coal mine goafs has not yet been established. Major challenges include strong structural heterogeneity, discontinuous fracture networks, scale dependence of equivalent parameters, and limited multiscale experimental data under coupled CO_2–water–rock–stress conditions. Therefore, establishing experimentally validated scale-transfer relationships remains an important direction for future research. These developments will provide an experimental basis for developing a multiscale theoretical framework for CO_2 storage in abandoned coal mine goafs.

4.2 Dynamic Stability Evaluation Methods Considering Reservoir–Caprock Evolution

Existing CO_2 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 CO_2 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, CO_2 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 method-

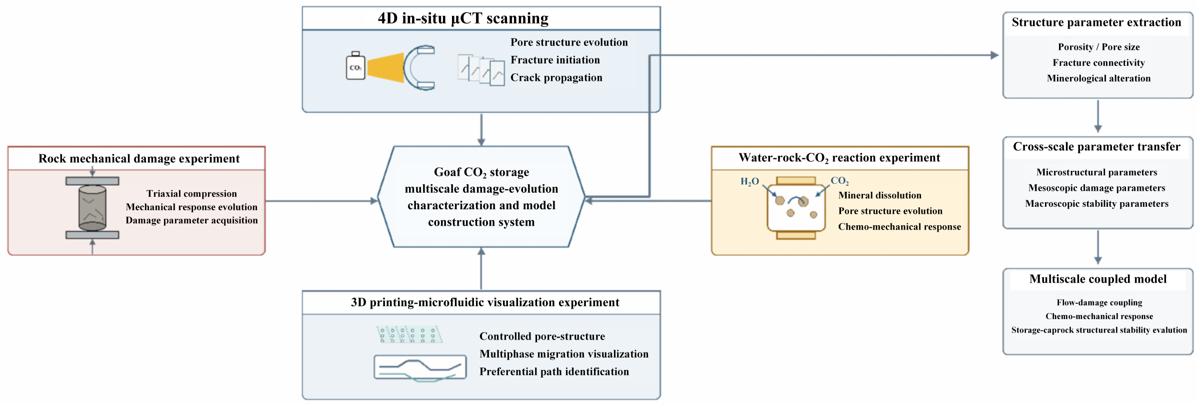

Fig. 4 Multiscale damage evolution characterization and coupled modeling framework for CO_2 storage in abandoned coal mine goafs

s 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 stability of CO_2 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 CO_2 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 CO_2 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.

Practical engineering applications of CO_2 storage in abandoned coal mine goafs also face significant constraints in site investigation and long-term monitoring. Detailed geological and mining records may be incomplete for some abandoned mines, making it difficult to accurately determine goaf geometry, overlying fracture distribution, and potential leakage pathways. In addition, the strong spatial heterogeneity of disturbed rock masses limits the representativeness of parameters obtained from a small number of boreholes or local measurements. Long-term monitoring is also challenging because direct access to abandoned underground spaces is usually limited, and monitoring points cannot be densely deployed. Therefore, reliable site characterization and safety evaluation should integrate historical mining records, borehole investigations, geophysical exploration, and long-term monitoring data. The integration of multiple data sources with multiphysics models can reduce uncertainties in geological characterization and improve the identification of potential leakage pathways and long-term storage risks.

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

CO_2 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, CO_2 storage theories established based on stable reservoir assumptions cannot be directly applied.

This study proposes that CO_2 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 CO_2 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

CO_2 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 CO_2 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 CO_2 storage and green transformation of mining areas.

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Conflict of interest

The authors declare no competing interest.

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