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Review

Prospect and technology of CO_2 storage in coal mine goafs

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Abstract: Carbon capture, utilization, and storage is a crucial technological approach to mitigating global warming. As a promising geological storage technology, CO_2 storage in coal mine goafs not only addresses the challenge of source-sink mismatch but also facilitates the resource utilization of abandoned coal mine goafs and shafts worldwide. However, ensuring the long-term sealing and integrity of the caprock and preventing CO_2 leakage remain the core challenges for this technology. This paper systematically summarizes and analyzes CO_2 storage in coal mine goafs from the perspectives of storage mechanisms, capacity evaluation, monitoring and early-warning systems, and multi-field coupling effects. The study reveals that establishing a real-time, systematic, and intelligent lifecycle safety assurance system is the key to overcoming the core challenges of CO_2 storage in coal mine goafs and achieving long-term safe and stable operation. This paper aims to provide a scientific basis for the development and application of CO_2 storage technology in coal mine goafs.

Keywords: CCUS; CO_2 geological storage; coal mine goafs; caprock integrity; risk monitoring

1. Introduction

Human activities have led to a sharp rise in atmosphere greenhouse gas concentrations, in the atmosphere, resulting in global warming and an increased frequency of extreme weather events (Calvin et al., 2024). Achieving carbon emission reductions has become a widely recognized consensus and an urgent task for the international community. The signing of climate agreements such as the Paris Agreement underscores the global commitment to emission reduction targets, with many countries setting goals to achieve carbon neutrality by mid-century (Bodansky, 2016; Rogelj et al., 2016). Currently, the global energy structure is rapidly transitioning toward cleaner and lower-carbon sources; however, fossil fuels will remain a significant component of the energy mix in many economies for a considerable period (Xie, 2021). Therefore, advancing the research and application of carbon capture, utilization, and storage (CCUS) technology is of great strategic significance for ensuring a secure and stable global energy transition (Bui et al., 2018; Davis et al., 2018).

As a key link in the CCUS technology chain, CO_2 storage aims to isolate the captured CO_2 from the atmosphere for a long time, which is an important technical means to achieve large-scale and permanent emission reduction (Dziejarski et al., 2023; Marchetti, 1977). The current mainstream storage methods include marine storage, mineralization storage, and geological storage (Zhao and Itakura, 2023). Among them, geological storage in deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams is widely regarded as the most promising way because of its relatively mature technology and large storage capacity (Bashir et al., 2024). Nevertheless, traditional CO_2 storage technologies often face practical challenges such as site selection complexities and geographical mismatches between major emission sources and suitable storage locations, commonly referred to as the "source-sink mismatch" (Nagireddi et al., 2023).

With the continuous advancement of CO_2 sequestration technology, CO_2 storage in coal mine goafs offers an innovative solution to address related challenges (Liu et al., 2023; Brodny, 2017). These storage sites are typically located near major CO_2 emission sources such as coal-fired power plants and coal chemical facilities, effectively mitigating the "source-sink mismatch" problem while enabling the resourceful utilization of underground spaces like goafs and abandoned mines. Although the global energy structure is transitioning to cleaner energy sources, fossil fuels will continue to play a significant role in the global energy system for a considerable period. As a key

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component of fossil energy, coal mining will result in the continuous increase in the number of goafs and abandoned mines. Research indicates that by 2030, underground spaces resulting from coal mining in China alone could reach 23.452 billion cubic meters, providing ample space for CO_2 storage (Xie et al., 2018).

Despite the promising potential of utilizing coal mine goafs for CO_2 storage, the unique geological characteristics of these artificially created structures introduce new technical challenges for geological storage. Current research tends to focus on summarizing the technology from specific aspects such as storage mechanisms, capacity assessment, or risk monitoring, while systematic reviews are still relatively rare. To bridge this gap, this paper conducts a comprehensive review of CO_2 storage in coal mine goafs based on traditional CO_2 storage technologies. The review focuses on storage advantages, storage mechanisms, capacity evaluation, risk monitoring, and the effects of multi-mechanism coupling. Furthermore, future research directions are discussed to offer valuable insights for the safe and large-scale engineering implementation of this technology.

2. Mainstream technologies of CO_2 storage

2.1 Marine storage

Marine storage is mainly based on the solubility of CO_2 in water, which is injected into the deep sea to dissolve it, or used to react with seawater to form carbonates (Sun et al., 2023). This technology has great storage potential in theory. However, long-term large-scale CO_2 injection may lead to pH changes of the deep-sea and impact marine ecosystems. In addition, it has a risk of the gradual release of dissolved CO_2 back to the atmosphere, so its environmental safety and long-term effectiveness are still controversial.

2.2 Mineral storage

Mineral storage was proposed by Seifritz in 1990 (Seifritz, 1990). By simulating the weathering process of natural rocks, natural ores or industrial waste residues rich in calcium and magnesium are used to react with CO_2 through in-situ or ex-situ mineralization pathways to form stable carbonate minerals to achieve long-term or permanent storage of CO_2 (Snæbjörnsdóttir et al., 2020; Kong et al., 2024(a); Kong et al., 2024(b)). The technology has high safety and stability, but it still faces technical bottlenecks such as slow reaction rate, high energy consumption, and high cost.

2.3 Geological storage

Geological storage is to inject supercritical or gaseous CO_2 into deep underground geological bodies and achieve long-term storage through natural trapping mechanisms. The main storage sites include deep saline aquifers, depleted oil and gas reservoirs, deep unminable coal seams, and basalts (Bao et al., 2024) (Fig. 1). Among them, the deep saline aquifer is widely distributed and has a large capacity, which is recognized as the most important CO_2 storage site in the world. The depleted oil and gas reservoirs have a clear geological structure, good sealing, and the injected CO_2 can be used to strengthen oil and gas exploitation (CO_2-EOR/EGR), which has both economic and environmental benefits. The deep unmineable coal seams utilize the property that CO_2 has a stronger adsorption capacity on coal matrix than methane, enabling CO_2 to be sequestered through displacement during coalbed methane extraction (CO_2-ECBM). Basalt, it is rich in the strata, offers better mineralization potential and lower CO_2 leakage risk (Kim et al., 2023).

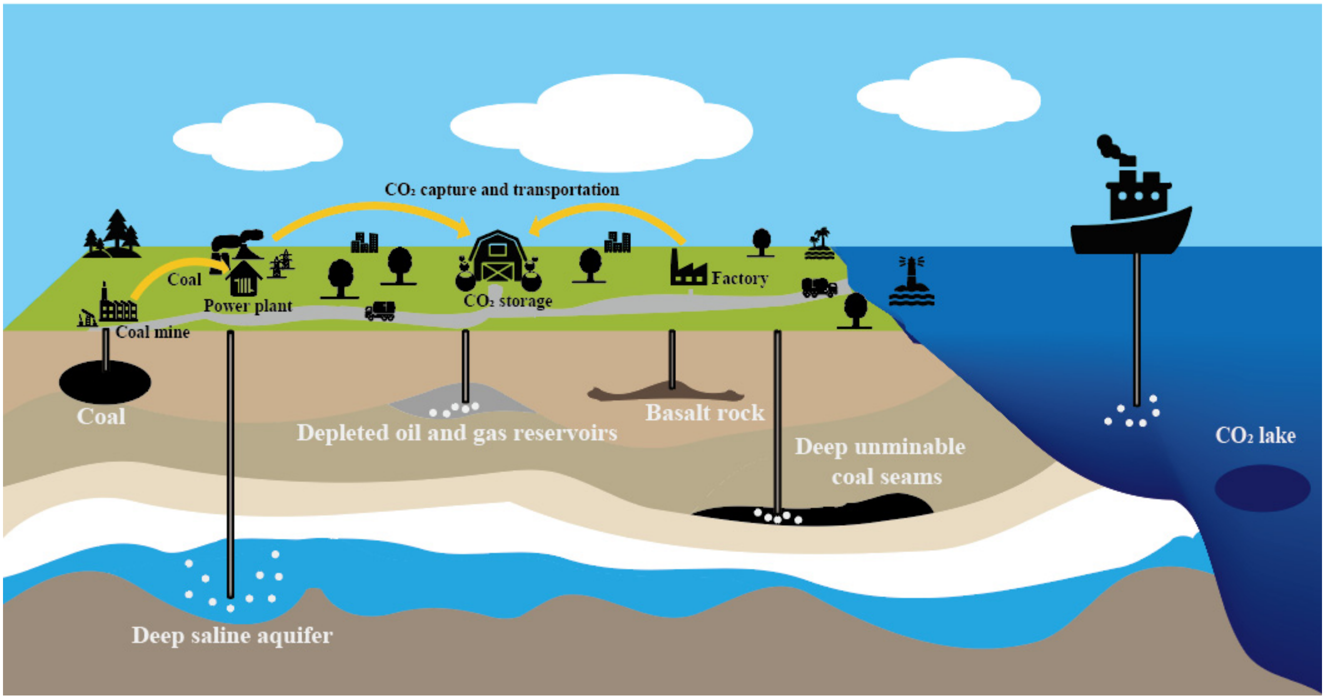

Fig. 1. Schematic diagram of CO_2 storage technology.

A number of geological storage demonstration projects have been carried out in the world, such as the Sleipner project in Norway (Torp and Gale, 2004), the K12-B project in the Netherlands (Vandeweijer et al., 2018), the San Juan Basin in the United States (Damen et al., 2005), and so on. China's Shenhua Ordos (Xie et al., 2015), Qinshui Basin (Zhou et al., 2013), Nanhai Enping 15-1 (Wang et al., 2024), and other projects have also successfully verified the feasibility of storage. The CarbFix project in Iceland has realized the rapid mineralization of CO_2 in basalt strata with a mineralization rate of more than 95%, showing the application potential of mineralization storage (Matter et al., 2011).

3. CO_2 storage in coal mine goafs

3.1 Advantages of coal mine goafs storage

Long-term coal mining has left behind a vast number of underground goafs and abandoned mines worldwide, providing unique opportunities for CO_2 storage in coal mine goafs (Lyu et al., 2022). Compared to traditional geological storage sites, these opportunities stem primarily from the inherent connection between the coal industry and CO_2 emissions.

The most significant advantage is that coal mine goafs are often geographically co-located with major industrial emission sources, such as coal-fired power plants and coal chemical facilities. This enables the capture and storage of CO_2 locally, fundamentally resolving the key cost-prohibitive issue of traditional storage, the "source-sink mismatch" (Huang et al., 2011). This geographical proximity, combined with the potential to retrofit and reuse existing mine infrastructure (such as shafts and tunnels), creates a highly compelling economic prospect by substantially reducing both transportation and initial capital investment costs.

Furthermore, goafs offer excellent physical conditions. Their vast storage space provides a solid physical foundation for large-scale deployment, while the detailed geological exploration data accumulated over long periods of mining significantly reduces uncertainty during the exploration process (Huang et al., 2014; Ding et al., 2023a). These data provide support for site screening, storage volume assessment, and long-term safe and stable operation.

3.2 Storage mechanism of coal mine goafs

The CO_2 storage in coal mine goafs involves utilizing the underground spaces formed by coal mining or the abandoned sealed underground spaces left behind after mining operations for CO_2 storage. The CO_2 storage mechanisms in coal mine goafs include structural trapping, sorption trapping, solubility trapping, and mineral trapping (Golding et al., 2011; Hameli et al., 2022) (Fig. 2). The effectiveness and dominance of these mechanisms are primarily influenced by the hydrogeological conditions within the goaf, particularly the degree of water saturation (Ali et al., 2022).

In unsaturated or partially saturated goafs, the presence of a continuous gas phase causes the initial diffusion and migration of CO_2 to be primarily controlled by gravity (Zhou et al., 2025). Due to its much higher density compared to air, CO_2 tends to accumulate in the lower sections of the caving zone and fractured zone, making structural trapping the dominant short-term storage mechanism. As the volume of injected CO_2 increases, the residual coal seams and collapsed rocks in the goafs provide additional storage space, facilitating sorption trapping (Ding et al., 2025; Cai et al., 2025).

At the same time, formation water within the goafs and surrounding rock layers plays a critical role in solubility trapping (Gilfillan et al., 2009; Abba et al., 2019). When CO_2 comes into contact with formation water, it dissolves to form carbonic acid, which lowers the pH of the water and further promotes the dissolution process. Over the long term, especially in fully saturated goafs, solubility trapping and mineral trapping work together (Romanov et al., 2015). The dissolved CO_2 in the formation water reacts with the surrounding rock layers, forming stable carbonates and achieving permanent fixation.

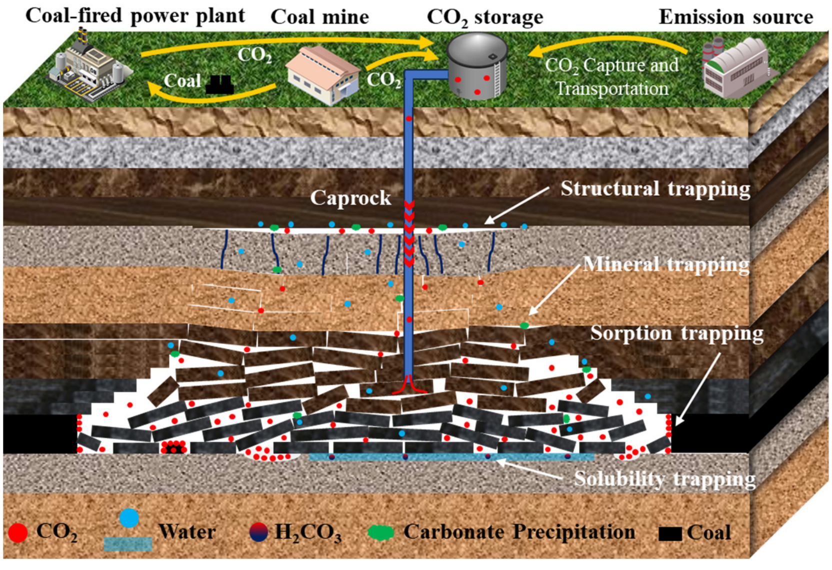

Fig. 2. CO_2 storage mechanism in mine goaf.

It is precisely this synergistic effect of multiple storage mechanisms that endows coal mine goafs with unique long-term safety and stability in CO_2 storage.

3.3 Evaluation of coal mine goafs storage capacity

The assessment of CO_2 storage potential in coal mine goafs is a critical step in evaluating their storage feasibility. The evaluation process typically progresses through multiple stages, starting with large-scale regional screening and advancing to detailed site-specific characterization (Shen et al., 2009). It requires the integration of various parameters, including the spatial geometry of the goaf, the heterogeneous distribution of porosity and permeability, residual coal content, and the dynamic hydrochemical properties of formation water (Ambrose et al., 2008; Bachu et al., 2007; He et al., 2025(a)). As coal mine goafs are artificially formed and exhibit high geological heterogeneity, their storage capacity assessment methods are often adapted from traditional geological storage techniques, primarily involving preliminary estimation using the volumetric method and refined evaluation through numerical simulation (Liu et al., 2021).

The volumetric method is one of the most fundamental and widely applied approaches for evaluating the effective storage capacity of geological structures (Goodman et al., 2011). This method estimates CO_2 storage capacity by calculating the effective storage space and combining it with the density of CO_2 under reservoir conditions. When assessing the CO_2 storage potential of coal mine goafs, the volumetric method involves calculating the effective total volume of structural spaces and rock fractures within the goaf, as well as analyzing the physical properties of CO_2 in its stable phase after injection. The key parameters include the effective total volume of the goaf, the porosity of the rock layers, the density of CO_2 under reservoir conditions, and the storage efficiency coefficient. However, during long-term storage, the porosity of the rock layers may be influenced by both physical processes and mineralization effects, leading to significant changes in the pore-fracture structure, which can affect the assessment results (He et al., 2025(b)). The storage efficiency coefficient, which quantifies the fraction of pore volume available for storage, can also significantly impact the storage capacity evaluation, especially in highly heterogeneous goaf environments (Ramadhan et al., 2025).

Therefore, defining appropriate parameter ranges for different goafs remains a key challenge in current research. This requires not only a comprehensive understanding of the geological characteristics of goafs but also the integration of long-term monitoring data to dynamically adjust the storage efficiency coefficient, thereby improving the reliability and scientific accuracy of the evaluation results.

For site-specific evaluations, the numerical simulation method offers a more refined and dynamic approach. It involves constructing detailed geological models that incorporate the heterogeneous properties of goafs, and solving coupled multi-physics equations (e.g., fluid flow, geomechanics, and geochemical reactions). This method simulates the complex processes involved in CO_2 injection and long-term storage, predicting the long-term diffusion and migration of CO_2, pressure evolution, the contributions of various trapping mechanisms, and potential geomechanical responses (Rasheed et al., 2020; Khudaida and Das, 2020; Machado et al., 2023). This enables precise assessments of storage capacity and long-term security. However, numerical simulation places high demands on the accuracy of geostatistical models and computational resources.

However, the numerical simulation method requires precise characterization of the multi-scale pore and fracture networks within the goaf, while the computational cost of long-term multi-field coupled simulations remains high. Therefore, future research should focus on the development of multi-scale hybrid models and their integration with machine learning techniques to reduce computational costs, enhance simulation accuracy and efficiency, and strengthen the connection between simulation and monitoring.

3.4 Monitoring and early warning system

Long-term security is the core factor determining whether CO_2 storage technology in a goaf can be applied in engineering. However, unlike natural geological formations, the overlying strata and caprock in goafs may experience migration, fracturing, and the development of fissures due to geological conditions and disturbances caused by coal mining. These factors reduce the airtightness and integrity of the caprock layer, forming potential CO_2 leakage channels (Mortezaei et al., 2021; Major et al., 2018). Therefore, the establishment of a whole life cycle risk monitoring and control system is the key to ensuring the safety and stability of CO_2 storage in the goaf.

The monitoring process should cover three stages: CO_2 injection, storage operation, and long-term stability after storage (Sori et al., 2024). At present, the monitoring technology of CO_2 storage mainly includes geophysical monitoring (Li and Zhang, 2024), such as microseismic monitoring, resistivity imaging technology, etc. Microseismic monitoring can detect microseismic events in real time, identify rock fracture propagation or fault activity, and thus evaluate caprock stability. Resistivity imaging technology can be used to track the spatiotemporal distribution and migration front of CO_2 plumes. Goertz-Allmann et al. (2017) conducted geomechanical reservoir characterization and caprock integrity assessment of the Decatur, Illinois, carbon capture and storage (CCS) demonstration project by monitoring microseismic events within the storage site. Geochemical monitoring (Ma et al., 2024), through regular collection of groundwater, soil gas, and surface gas samples, analysis of pH, ion concentration, and carbon isotope composition changes, identifies possible leakage signals. Yang et al. (2017) combined field experiments and numerical simulations, accounting for diffusion, soil water dissolution, and soil respiration, to develop a CO_2 dynamic model. They proposed using CO_2 concentration and stable carbon isotope ratios as indicators for leakage detection in geological storage sites. Injection and abandoned wells are potential leakage pathways. Distributed optical fiber sensors combined with pressure, temperature, and flow rate monitoring techniques provide real-time assessments of wellbore operations and their integrity. Chen et al. (2025) utilized distributed fiber optic sensors to monitor parameters such as pressure, temperature, and flow rate in CO_2 injection wells for real-time leakage monitoring. Surface deformation monitoring (Vasco et al., 2020), using InSAR, GPS, and precision leveling technology to capture ground subsidence caused by changes in gas pressure. Zhang et al. (2022), using the Shizhuang Town CCUS project in Shanxi Province, China, as an example, combined UAV technology with Interferometric Synthetic Aperture Radar (InSAR) technology to generate a high-resolution Digital Elevation Model (DEM) for the storage site and monitored surface deformation in the area following CO_2 injection.

Although current monitoring technologies are relatively mature, their application in coal mine goafs still faces challenges due to the heterogeneity of rock strata and complex fracture networks. The key issues are distinguishing CO_2 injection-induced deformation signals from background noise and integrating point-based measurements (e.g., wellbore sensors) with large-area monitoring technologies (e.g., InSAR) to develop predictive models for CO_2 injection in goafs.

To address these challenges, future efforts should focus on advancing sensor technology, data fusion with intelligent algorithms, and dynamic feedback mechanisms (Yan et al., 2021). Specifically, this includes developing low-cost, high-performance sensor networks suitable for the complex environment of goafs, leveraging artificial intelligence to integrate multi-physics data for real-time risk assessment and uncertainty reduction. Additionally, establishing a closed-loop system for real-time monitoring and model updates can transform monitoring from passive observation to proactive management. Promote the development of an "integrated intelligent monitoring and early warning platform" to ensure the long-term safety and stability of CO_2 storage in coal mine goafs.

3.5 Multi-field coupling effect

The core of the research on CO_2 storage in coal mine goafs is to accurately solve the thermal-hydro-mechanical-chemical (THMC) multi-field coupling problem involved in the process of CO_2 injection and storage. However, this process spans large temporal scales and is highly complex, making it difficult to fully reproduce under traditional laboratory conditions; consequently, numerical simulation has become an essential tool for exploring THMC behavior.

Currently, the THMC coupled simulation of CO_2 storage in coal mine goafs faces two major challenges. The first is the characterization of extreme heterogeneity (Li et al., 2024). The mining-induced fracture networks within goafs and their overlying strata exhibit multi-scale and highly heterogeneous characteristics. The diffusion and migration rates of CO_2 vary significantly across regions with different permeabilities. High-permeability areas may become potential CO_2 leakage pathways, posing a threat to the sealing integrity of the caprock. Therefore, constructing accurate geometric and physical models is a prerequisite for simulating this storage technology. The second challenge is the efficient computation for large-scale, long-term multi-field coupling. The CO_2 storage process may span decades or even millennia, making long-term THMC coupled simulations computationally expensive (Zhou et al., 2022).

To address these challenges, existing studies often adopt simplified representations such as equivalent continuous media or discrete fracture networks models, and use multi-scale methods or decoupling algorithms to improve computational efficiency. Numerical simulation tools such as $FLAC^{3D}$, TOUGH series and COMSOL Multiphysics have been widely applied in related research.

For instance, $FLAC^{3D}$, with its powerful finite difference solver, excels at handling large deformations and complex rock mechanical failure mechanisms, making it a key tool for analyzing the stability of the overlying strata and caprock. Gou et al. (2016) used the $TOUGH2^{MP}$-$FLAC^{3D}$ simulator to conduct a numerical study on a three-dimensional (3D) geological model of the natural gas reservoirs in the North German Basin. The TOUGH series is specifically designed for simulating non-isothermal, multiphase, and multicomponent fluid and heat flows in porous and fractured media, and is crucial for predicting CO_2 diffusion and migration. Sun et al. (2025) used the TOUGH2/ECO2N simulation software to conduct numerical simulations of CO_2 geological storage in the target area of the Yellow River Delta, and proposed a comprehensive framework for the site selection and potential evaluation of carbon dioxide geological storage. COMSOL Multiphysics provides a high degree of flexibility in customizing equations, rendering it particularly powerful for exploring novel coupling mechanisms at the research stage. Based on the actual geological conditions of the experimental coal mine in Huangling mining area, Ding et al. (2023b) used COMSOL Multiphysics to conduct numerical simulation of CO_2 injection in the old goaf area, and derived the vertical injection points and monitoring well deployment methods that are conducive to improving the CO_2 sequestration in the old goaf area.

In recent years, research combining numerical simulation with machine learning has developed rapidly, providing new pathways to address critical bottlenecks such as high computational costs and parameter uncertainties. By utilizing surrogate models like neural networks, this approach can replace expensive numerical computations, enabling large-scale parameter analysis and risk quantification (Lin et al., 2025). Meanwhile, cutting-edge technologies such as Physics-Informed Neural Networks (PINNs) hold the potential to directly extract and learn governing equations from data, offering a novel perspective for understanding complex constitutive relationships (Wang et al., 2024). These explorations are set to advance the research of CO_2 storage in coal mine goafs from traditional numerical simulations to more intelligent and efficient predictive analyses.

4. Challenges and prospects

Although the CO_2 storage in coal mine goafs shows a broad application prospect, it still faces numerous challenges from mechanisms, technology, policy, and economics. In order to promote the development of the technology, future research should establish a systematic framework from fundamental theory to engineering application.

1) Mechanisms for Ensuring Long-term Safety and Stability

The primary challenge remains the long-term sealing integrity of the caprock. The key to addressing this core issue lies in accurately predicting the evolution of the complex fracture network between the rock and caprock under the multi-field coupling of THMC. This requires significant progress in characterization and predictive modeling to ensure the long-term safety and stability of storage.

2) Promoting technological innovation

Develop low-cost, high-performance caprock sealing technologies and fracture-plugging materials suitable for coal mine goafs environments, and research and develop a real-time, intelligent monitoring and early warning platform. A technological shift from passive management to proactive prevention of potential risks in the storage process is underway.

3) Improving policy and legal standards

Compared to traditional geological storage technologies, CO_2 storage technology in coal mine goafs is still in its infancy in terms of supportive policies and regulatory frameworks. Promoting the global establishment of relevant regulations and incentive policies is essential for achieving large-scale, integrated coal mine goafs storage projects. A robust policy framework and supporting measures will facilitate the widespread adoption and scaling of this technology.

4) Exploring multi-mode economic integration

Actively explore new CO_2 storage models, such as combining them with coal mine goafs management and mining solid waste resource utilization, transforming a single carbon storage project into a comprehensive underground space resource utilization project, and significantly improving the social and economic benefits of the project.

5. Conclusions

CO_2 storage technology in coal mine goafs offers a highly promising pathway for achieving large-scale carbon emission reductions. Its unique advantage lies in effectively addressing the common "source-sink mismatch" challenge in traditional geological storage while enabling the resource utilization of coal mine goafs and abandoned mines. This paper systematically summarizes and analyzes the research progress of CO_2 storage technology in coal mine goafs from the perspectives of storage mechanisms, capacity evaluation, monitoring and warning systems, and multi-field coupling effects. The findings indicate that, despite its significant advantages over traditional geological storage technologies, ensuring the long-term sealing integrity of the caprock remains the core challenge in the engineering application of coal mine goafs CO_2 storage, as it is an anthropogenically modified geological body.

To address this critical challenge, future research and applications should focus on building a real-time, systematic, and full-lifecycle safety assurance system. By transitioning CO_2 storage in coal mine goafs from passive observation to proactive prediction and prevention, the long-term safety and stability of the storage process can be ensured. Furthermore, efforts should be made to accelerate large-scale engineering demonstrations, establishing this technology as a safe, reliable, and essential component of the global CCUS system.

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Conflict of interest

Given the role as Editorial Board Member, Xiangguo Kong had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-assisted Technologies

No AI tools were utilized for this paper.

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