ACS OMEGA

http://pubs.acs.org/journal/acsodf

Review

Influence Factors and Feasibility Evaluation on Geological Sequestration of CO_2 in Coal Seams: A Review

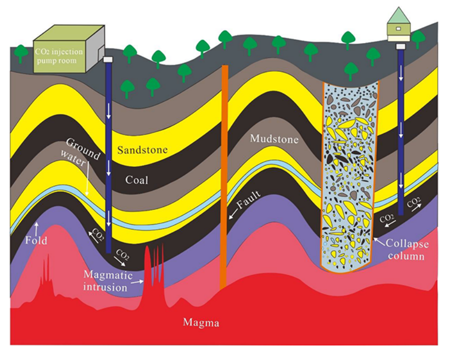
Meng Wu,* Yong Qin,* Yuanyuan Zhang, Shifei Zhu, Guchun Zhang, Fengjuan Lan, Xuejuan Song, Lele Feng, and Yunhu Qin

Cite This: *ACS Omega* 2023, 8, 16561−16569

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: The geological sequestration of CO_2 in coal seams holds significant implications for coalbed methane development and greenhouse gas mitigation. This paper examines the principles, influencing factors, and evaluation methods for geological CO_2 sequestration in coal seams by analyzing relevant domestic and international findings. Suitable geological conditions for CO_2 sequestration include burial depths between 300 and 1300 m, permeability greater than 0.01×10^{-3} μm^2, caprock and floor strata with water isolation capabilities, and high-rank bituminous coal or anthracite with low ash yield. Geological structures, shallow freshwater layers, and complex hydrological conditions should be avoided. Additionally, the engineering conditions of temperature, pressure, and storage time for CO_2 sequestration should be given special attention. The feasibility evaluation of CO_2 geological storage in coal seams necessitates a comprehensive understanding of coalfield geological factors. By integrating the evaluation principles of site selection feasibility, injection controllability, sequestration security, and development economy, various mathematical models and “one vote veto” power can optimize the sequestration area and provide recommendations for rational CO_2 geological storage layout.



1. INTRODUCTION

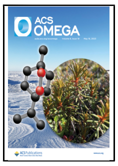
The greenhouse effect, a term coined in 1827 by Baron Jean Baptiste Joseph Fourier, introduced and qualitatively discussed the atmosphere's greenhouse effect.[1] By 1861, John Tyndall, an Irish chemist, discovered that the atmosphere contained a few triatomic molecules such as CO_2, H_2O, CH_4, N_2O, and O_3, which exhibited a greenhouse effect.[2] Since the Industrial Revolution, human consumption of fossil energy sources and the release of greenhouse gases, primarily CO_2, have exceeded natural regulatory capacity, leading to a sharp increase in atmospheric CO_2 deposition.[3] Large CO_2 emissions exacerbate global warming, causing glacier melting, rising sea levels, significant declines in plant and animal species, and an increased frequency of extreme weather events such as droughts and floods.[4,5]

Reducing CO_2 emissions has become a critical issue for scientists worldwide.[6] Coal, as a natural CO_2 adsorbent, exhibits two to three times the adsorption capacity for CO_2 compared to CH_4.[7,8] Geological sequestration of CO_2 in coal seams represents an effective measure to decrease atmospheric CO_2 concentration and alleviates the greenhouse effect.[9] Additionally, CO_2 can be utilized to displace CH_4, improving coalbed methane (CBM) recovery, increasing economic benefits, and reducing sequestration costs.[3−5] Pilot experiments and theoretical studies have been conducted in the United States' San Juan Basin, Canada's Alberta Basin, Japan's Ishikari, Germany's Krmovic, Poland's Silesian Basin, and China's Qinshui and Ordos Basins.[4,9] However, limitations exist in the geological conditions suitable for CO_2 sequestration in coal seams.[7,9,10] Moreover, uncontrollable CO_2 injection into coal seams and technical constraints collectively influence the feasibility of geological CO_2 sequestration.[11] This paper reviews the influencing factors of geological CO_2 sequestration in coal seams and their feasibility evaluation based on relevant domestic and international literature, aiming to provide a theoretical foundation for carbon reduction projects.

2. PRINCIPLE OF GEOLOGICAL SEQUESTRATION OF CO_2 IN COAL SEAMS

Coal seams exhibit a significant dual-pore structure and possess substantial gas adsorption and storage capacity. The dual-pore structure comprises primary micropores, secondary macropores, and even fractures, which form in coal seams under the influence of coalification and geological processes.[12] These

Received: February 20, 2023
Accepted: April 24, 2023
Published: May 3, 2023



ACS Publications

© 2023 The Authors. Published by American Chemical Society

https://doi.org/10.1021/acsomega.3c01148

structures provide the necessary sites and pathways for CO_2 storage and transport.[13] The gas adsorption capacity of coal seams is dependent on specific temperature and pressure conditions, and the coal seam offers a stable storage environment for CO_2.[14] The adsorption properties of coal seams involve interactions between CO_2 and the coal surface, which are manifested by differences in stress between surface and internal molecules in the dual-pore space of the coal matrix, leading to the formation of surface potential energy.[15] Consequently, the concentration of CO_2 on the coal pore walls increases, forming adsorption and releasing adsorption heat.[15] Initially, CH_4 molecules are bound to the coal matrix surface via weak van der Waals forces. Upon CO_2 injection, CO_2 molecules compete for adsorption sites on the coal surface due to their stronger affinity, reducing the surface free energy and displacing CH_4 from its original position. Furthermore, CO_2 lowers the partial pressure of CH_4, prompting the desorption of additional CH_4 to achieve a new pressure equilibrium.[16] From a quantum chemistry perspective, the adsorption potential well for CO_2 molecules on the coal seam is considerably larger than that for CH_4 molecules.[17]

Geological sequestration of CO_2 in coal seams and enhanced coalbed methane (CO_2-ECBM) recovery are employed to achieve carbon sequestration.[9,10,18] CO_2 geological sequestration in coal seams encompasses two major systems: injection and extraction. Injection involves pumping captured CO_2 into designated coal seams using an injection pump, transforming the coal bed methane from an adsorbed state to a free state. Extraction refers to the recovery of CBM through a production well and subsequent water treatment, component separation, and gas compression, ultimately enabling the recovery and utilization of CBM (Figure 1).[5,19]

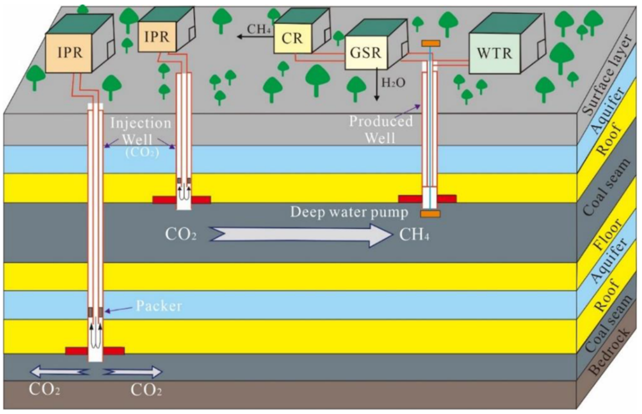


Figure 1. Schematic diagram of carbon dioxide geological storage in coal seams and exploitation of CBM. IPR, injection pump room; CR, compressor room; GSR, gas separation room; WTR, water treatment room.

3. GEOLOGICAL FACTORS

3.1. Geological Structure. The variety of geological structures encompasses faults, collapse columns, folds, and magmatic intrusions (Figure 2). Both faults and collapse columns disrupt the continuity of the seam,[20] particularly the horizontal integrity of caprock, which increases the risk of CO_2 diffusion in coal seams during geological evolution.[21] Moreover, faults and collapse columns frequently serve as diversion channels, posing a threat to the long-term storage of CO_2.[22]

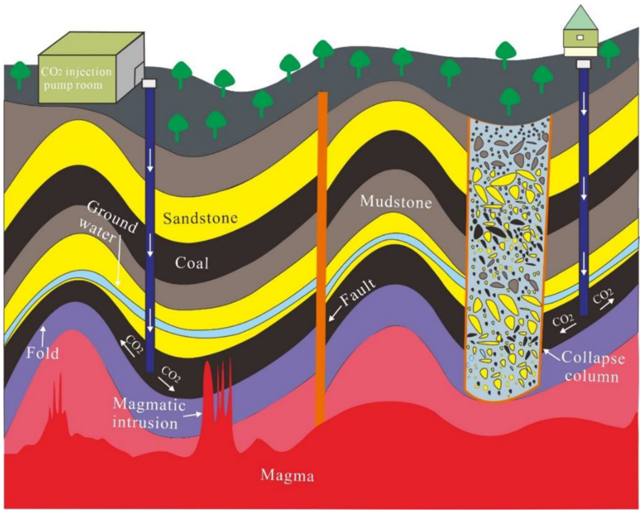


Figure 2. Schematic diagram of the geological structure affecting CO_2 sequestration.

Most notably, well-developed coal seams predominantly consist of mylonitized coal and granulated coal with extremely low permeability, which can facilitate the structural migration of CO_2 and form an abnormally high-pressure zone.[23] To a significant degree, the origins and characteristics of a fault determine whether it functions as a channel or barrier in the geological sequestration of CO_2.[24] Generally, faults subject to pressure torsional forces contribute to CO_2 containment, while tensional faults are predisposed to CO_2 leakage.[21]

Successful CO_2-ECBM test sites, both domestic and international, exhibit underdeveloped fractures and tectonic stability.[21,23] The magnitude of folds should not surpass half of the coal seam thickness, as this could compromise the stability of the coal seam and the efficiency of CO_2 injection.[25] Furthermore, magmatic intrusions impair the coal seam structure and continuity.[20] Consequently, site selection for the geological sequestration of CO_2 in coal seams should circumvent areas with complex structures.[26]

3.2. Occurrence Characteristics of Coal Seams. The occurrence characteristics of coal seams are decisive indicators for determining the CO_2 sequestration potential,[7] which include coal seam thickness, dips, and burial depths.[20,21]

On the premise that coal seams have sufficient capacity to store CO_2, nonminable coal seams with small thickness, high sulfur, and high mining risk should be selected in order to save and utilize coal resources. Simultaneously, the coal seam is characterized by property permeability and adsorption, and the upper overlayer is capable of ensuring the long term stability and safety of CO_2 sequestration.[21,26,27] Coal seams with large thicknesses and small spacing should be selected from the perspective of CO_2-ECBM and the safety of CO_2 sequestration. Theoretically, the coal seam thickness is more than 8 m.[22] This not only depends on the larger space for storing CO_2 in thick coal seams but also relates to the influence of thickness on the permeability of coal seams where CO_2 displaces CH_4.[25] The coal seams with small dips are characterized by good continuity and stability, which help ensure the diffusion and sealing of CO_2 in the coal seams.[24,27]

As the burial depth of the coal seam increases, the porosity and permeability of the caprock gradually decrease.[26,27] From an economic standpoint, the burial depth of the coal seam should not surpass 3300 m.[28] Concurrently, the current status of CO_2 geological storage-related projects worldwide is presented in Table 1.[21,27,29] In summary, the suitable burial depth of coal seams for CO_2 storage ranges from 300 to 1300 m.

Table 1. Projects of CO_2 Geological Sequestration in the World

Project name	Country	Location	Total storage capacity (10^3 t)	Depth (m)
Allison Unit	USA	New Mexieo	277	950
MGSC-ECBM	USA	IIlinois	0.7	273
PCORLingnite	USA	North Dakota	-	500
SECARBC Central Appalaehian	USA	Weat Virginia	0.9	490−570
SECARBC Black Warrior Basin	USA	Alabanla	0.9	460−470
SWP Sanjua	USA	New Mexieo	35	910
Lignite Field Validation	USA	Burke County	0.09	335
Black Warrior Basin Coal	USA	Tuscaloosa County	0.252	287−548
Marshall County	USA	Marshall County	4.5	400−530
Virginia Central Appalachian Basin Coal Test	USA	Russell County	0.9	427−671
Allison Unit, San Juan Basin	USA	Southern New Mexico	336	945
Pump Canyon, San Juan Basin	USA	San Juan Basin	16.699	918
Tanquary Farms	USA	Wabash County	0.0923	274
Buchanan County	USA	Buchanan County	1.47	274−671
FBV 4A MicroPilot	Canada	Alberta	0.18	1260
CSEMP	Canada	Alberta	10	430
RECOPOL	Poland	Kaniow	0.76	1050−1090
RECOPOL	Poland	Kaniow	0.692	1012−1076
Yuban Project	Japan	Ishikari Coal Basin	0.884	890
Qinshui Basin ECBM	China	Southern Shizhuang CBM Block	0.192	478
Qinshui Basin ECBM	China	Northern Shizhuang CBM Block	0.234	923
APP ECBM	China	Liulin CBM Block	0.46	560
Qinshui Basinmultiple wells	China	Northern Shizhuang CBM Block	4.491	972

3.3. Surrounding Rock. Roof-floor strata, a stable coal seam, is an effective guarantee for realizing the geological storage of CO_2.[22] In order to prevent vertical dispersion of CO_2 and reduce the percolation and diffusion of CO_2, the overlapped effective strata ensure that more of the CO_2 is found in the coal seams within a certain geological time scale while maintaining the balance of strata pressure and phase state.[20,21] The developmental level, mechanical properties, and distribution range of caprock directly affect the advantages and disadvantages of CO_2 storage and site selection in coal seams.[32,33] Rock formations with low permeability, undeveloped fractures, certain thickness, continuity, and toughness, such as paste salts, mudstones, and shales, are suitable as caprock for CO_2 geological sequestration.[23,34] The increase of reservoir pressure after the injection of CO_2 into the coal seam can easily induce microcracking or fissions in the coal seam roof-floor strata, thus disrupting the closeness of caprock.[25,33] Simultaneously, it is easy for the CO_2 to form gas channeling when a large amount of CO_2 is injected into the coal seam. It will cause the thin caprock to be breached by the CO_2 injection pressure and cause leakage.[21] Therefore, the geological site selection of CO_2 for coal seams should give priority to strata with favorable reservoir-cap assemblage.[22,24,27] Moreover, caprock is characterized by continuous spatial distribution, relatively large thickness, completeness, impermeability, and nonpenetrating brittle fracture.[22]

3.4. Physical Properties. Porosity is a critical factor influencing the CO_2 sequestration capacity of coal seams.[25,34] Higher porosity corresponds to a greater CO_2 sequestration capacity within the coal seams.[24] When coal seams contain a substantial amount of water, CO_2 and H_2O within the coal seam combine to form H_2CO_3, which leads to the dissolution of minerals and an increase in the number and volume of pores.[35] This process may even result in the formation of secondary dissolution fractures. However, the dissolution of carbonate cement causes the release of numerous particles that block the pores, ultimately reducing porosity.[36]

Permeability is a key determinant of the feasibility of CO_2 injection into coal seams and the containment capacity of the caprock.[21,29] An elevated permeability rate and a well-developed fissure system promote CO_2 injection, facilitating the entry of CO_2 into coal seam pores.[23,37] Furthermore, numerical simulations investigating CO_2 displacement of CBM have demonstrated that CO_2 sequestration is suitable for low permeability coal seams.[38] In thin or discontinuous coal seams, mudstone with low permeability can hinder overall coal seam permeability.[26] A medium permeability range (1×10^{-3}−5×10^{-3} μm^2) is favorable for the replacement of CBM by CO_2.[37] Deep coal seams should have a minimum permeability of 0.01×10^{-3} μm^2 to ensure effective CO_2 injection.[39]

Alterations in coal seam permeability result from a combination of factors such as temperature, gas adsorption/desorption, and pore pressure.[22,38] Concurrently, the volume fraction of the CO_2/CH_4 gas mixture shifts during movement, affecting coal seam distribution and permeability.[47] Expansion strain exerts some control over permeability.[40] In the early stages of low permeability, the dissolution of calcite veins contributes to increased permeability.[41] However, the presence and distribution of undissolved salt precipitates within the pore structure can lead to a 21%−66% reduction in permeability.[42] Therefore, permeability is the primary factor influencing the geological sequestration of CO_2 in coal seams.

3.5. Coal Rank. In general, vitrinite reflectance progressively increases, and the coal's capacity to adsorb CO_2 correspondingly grows.[43,44] Among various coal ranks, the CO_2 absorption order is as follows: long-flame coal < gas coal < coking coal < anthracite.[37] Lignite and low metamorphic bituminous coals exhibit high permeability.[26] The adsorption capacity of lignite for CO_2 is approximately 10 times that of CH_4;[22] however, its shallow burial depth renders it unsuitable for CO_2 storage.[17] Domestic and international researchers have investigated the competitive adsorption effect of CO_2/CH_4 on coal through experiments and molecular simulations, finding that the competitive adsorption ratio of CO_2/CH_4 declines as coal rank increases.[45] By studying the competitive adsorption of CH_4 on three different coal-rank coals, the selective competitive adsorption of CO_2 on CH_4 decreased with increasing coal rank and water content.[46] The absorption performance of CO_2/CH_4 for coals with varying degrees of metamorphism was analyzed, revealing that higher coalification led to an increased CH_4 displacement rate under low pressure.[16] A higher degree of coalification results in a greater propensity for desorption when driving CBM with supercritical CO_2 displacement for different coal-rank coals, subsequently enhancing CBM recovery.[47,48] The desorption−diffusion of CH_4/CO_2 within different coal-rank coals is associated with the internal surface properties and pore structure of coal micropores.[49,50] At the same effective stress, coal seam permeability during supercritical CO_2 percolation gradually diminishes with increasing coal metamorphism (Figure 3).[50]

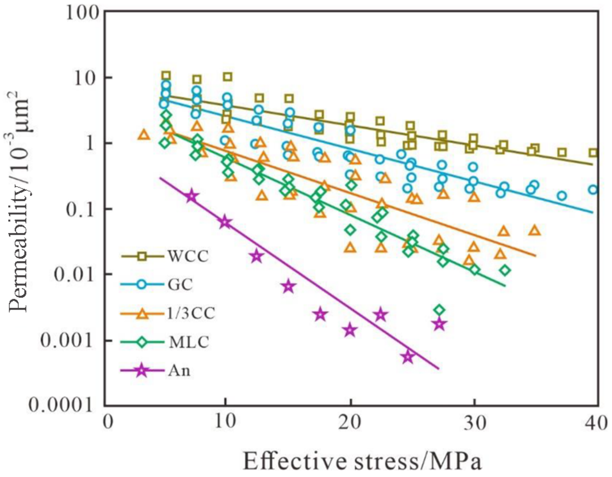


Figure 3. Relationship between permeability and effective stress of coal seams under different coal rank conditions. WCC, weak caking coal; GC, gas coal; 1/3CC, 1/3 coking coal; MLC, meager-lean coal; An, anthracite.

Additionally, the expansion deformation of the coal seam decreases with increasing coal rank when it adsorbs the same amount of CO_2.[51] This phenomenon is linked to "significant variations in the content and distribution of organic and mineral components in coals of different ranks, resulting in strong heterogeneity in mesomechanical properties".[52,53]

3.6. Coal Quality.

Moisture can diminish the capacity of anthracite to adsorb CH_4/CO_2.[51] However, the coal's ability to absorb CH_4/CO_2 remains virtually unaltered by water once the coal's water content surpasses the equilibrium water content.[52] This phenomenon is associated with the gas adsorption capacity of CH_4/CO_2, as water molecules preferentially form hydrogen bonds with oxygen-containing functionalities, such as carbonyl, hydroxyl, and carboxyl groups on the coal surface.[53] In the presence of high water content, supercritical CO_2 can extract oxygen-containing functional groups from the coal surface, altering its functional group structure and mechanical properties.[20,54] This process is evidenced by the formation of H_2CO_3 upon the dissolution of supercritical CO_2 in water; the dissolution of calcite, potassium feldspar, and other minerals present in primary fractures; the reopening of filled fractures;[55,56] and an increase in micropore volume within macropores and microcrystalline structures.[57,58] Fluids within the coal seam throat disrupt CO_2 continuity, decreasing its contact area with the coal surface and significantly reducing coal's CO_2 adsorption capacity.[59] Supercritical CO_2's plasticizing effect induces a transition of the coal matrix from a glassy to rubbery state, reducing the coal's rigidity and internal friction angle and ultimately decreasing its resistance to slide deformation.[60] Local mechanically weak regions are typically the initial cracking sites within coal petrography.[61] Moreover, the more mineral matter present in the coal, the less CO_2 gas is adsorbed.[27] High ash yield coal cleats and fission filled with minerals reduce the permeability and impair the rate of CO_2 displacement of CH_4.[37] Consequently, a lower ash yield coal seam is more suitable for CO_2 sequestration. The smaller the contact angle of the coal seam pore surface, the larger the breakthrough pressure gradient and the greater the pressure difference to be overcome in the initial stage of supercritical CO_2 displacement of water.[62] This indicates that salt precipitation can block the entire forked throat, leading to a decline in permeability when the coal seam pore surface is hydrophilic and neutral. However, when the pore surface is hydrophobic, salt precipitates occupy only a small pore space, and the permeation rate remains virtually unchanged.[63]

The coal surface functional group is the decisive factor for adsorption performance within the coal's large molecular structure.[64] For instance, the adsorption energy of various functionalized structures on CH_4/CO_2 was investigated using density functional theory, revealing that the adsorption energy of CO_2 (−50.56 kJ/mol) in the pyridine nitrogen-functionalized structure is greater than that of CO_2 (−14.71 kJ/mol) in the pyrrole nitrogen-functionalized structure.[65] Furthermore, the oxygen- and nitrogen-containing functional groups on the coal surface exhibit a stronger affinity for CO_2 compared to CH_4.[66,67] Among these, the order of adsorption energy for CO_2 in different functionalized structures is as follows: C-layer (−32.54 kJ/mol) < carbonyl-layer structure (−33.43 kJ/mol) < hydroxy-layer structure (−34.06 kJ/mol) < carboxyl-layer structure (−36.33 kJ/mol).[65] Therefore, the surface properties of the coal reservoir play a critical role in determining the efficiency of CO_2 displacement of CH_4 and the geological storage capacity.

3.7. Hydrogeology.

The CO_2-ECBM effect is intimately connected to hydrogeological conditions. Suitable hydrogeological conditions serve as a foundation for the long-term, safe sequestration of CO_2.[21] For instance, unstable hydrogeological conditions may compromise the integrity of CO_2 sequestration, while stable hydrogeological conditions can generate a hydrostatic closure that promotes CO_2 sequestration.[22] The larger the water volume in the aquifer, the closer the groundwater flow direction aligns with the coal seam tendency, and the more stringent the geological sequestration of CO_2 conditions become.[25] Ideal aquifer water quality necessitates a water isolation layer between the CO_2-injected coal seam and the roof and floor strata's water seam, ensuring that the water isolation layer's thickness will not compromise its functionality even after the top layer collapses.[23] In cases where groundwater exists in a reduced environment and consists of highly salinized $CaCl_2$-type brine, the groundwater layer exhibits favorable conditions for geological sequestration of CO_2.[51] Moreover, the higher the water content in the coal seams, the weaker the geological storage capacity of CO_2 in the coal seams.[68] To avert CO_2 leakage that could contaminate freshwater layers, CO_2 geological sequestration sites should be located far from shallow freshwater layers.[69]

4. ENGINEERING FACTORS

4.1. Temperature.

Temperature is an important parameter that affects the adsorption of CO_2 in coal seams. Jiang and

Ozdemir demonstrated that the adsorption of CO_2 in coal is an exothermic reaction through isothermal adsorption tests of CO_2 in coal seams at different temperatures.[37,70] Meanwhile, as the temperature increases, the adsorption capacity of CO_2 decreases.[37]

Supercritical CO_2 permeability within coal seams decreases as temperature increases when the volumetric stress applied to the coal seam is 36 MPa.[71] At 12.7 MPa, CO_2 displacement CH_4 tests at 35 °C, 45 °C, and 55 °C were conducted on lean coal from the Tunliu mine in Shanxi Province using an ISO-300 isothermal adsorber.[72] Results show that the volume fraction of the supercritical CO_2 adsorbing phase increases with temperature, while the CH_4 adsorbing phase decreases with temperature.[66−73] This occurs because gas absorption processes release calories, and rising temperatures not only inhibit gas adsorption but also activate CO_2 molecules.[65,66] This encourages gas collection at the coal matrix interface and reduces CH_4 adsorption,[72] indicating that supercritical CO_2 effectively enhances internal coal sample cracking and achieves high CH_4 recovery through CO_2 displacement at 35 °C.[67]

4.2. Pressure. During CBM extraction, CH_4 recovery increases with CO_2 injection pressure, but the contribution rate of increasing CO_2 injection pressure gradually diminishes through the expansion of the Langmuir equation and numerical simulation.[51] At low desorption pressures, CO_2 occupies high-energy adsorption positions in anthracite micropores and large mesopores.[74] As pressure continues to rise, CO_2 at low-energy adsorption sites in anthracite gradually increases until the coal pore inner surfaces are completely covered, forming a multimolecular layer.[75] Furthermore, CO_2/CH_4 absorption by coal-rock increases as pressure rises in a supercritical state, and the adsorption growth rate of coal petrography gradually decreases after pressure continues to increase.[45,76] According to the Hoek−Brown criterion,[3] the internal fissile structure of coal petrography compresses or even closes under high confining pressure, resulting in decreased permeability and reduced CO_2 adsorption space. Surrounding rock pressure increases, and axial strain rates of different coal ranks decrease with injection pressure (Figure 4).[48,50] This observation suggests that the confinement pressure significantly inhibits the weakening of the mechanical properties of CO_2 injected in coal.[15−17,77]

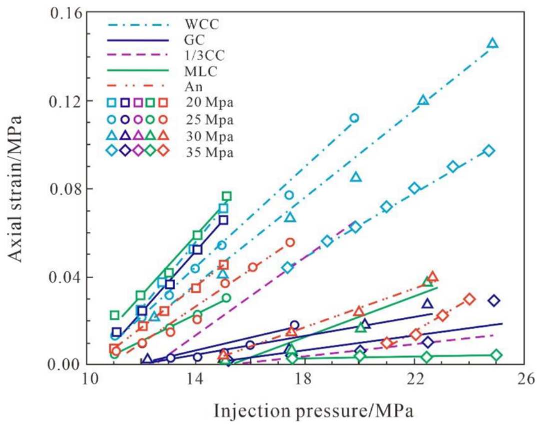


Figure 4. Relationship between axial strain and injection pressure of coal seams under different coal rank and confining pressure. WCC, weak caking coal; GC, gas coal; 1/3CC, 1/3 coking coal; MLC, meager-lean coal; An, anthracite.

4.3. Time. Temporal variations in CO_2 sequestration within coal seams can be classified into short-term adsorption sequestration and long-term CO_2 dissolution, ion reactions, and mineralization sequestration.[8] Prolonging the duration substantially enhances the safety and reliability of geological CO_2 sequestration.[78] This is primarily due to the unsaturated energy present on the pore surface of the coal seam, which facilitates the generation of van der Waals forces between nonpolar molecules, enabling the coal seam to adsorb and mitigate CO_2 emissions.[10] Moreover, secondary CO_2 sequestration reactions are slow, persistent, and constrained by temperature and pressure, preventing the rapid release of large quantities of sequestered CO_2.[8] As time elapses following CO_2 exposure, primary storage transitions to secondary storage, characterized by bound, dissolved, and mineralized forms.[79] This is exemplified when CO_2 is injected into a coal seam with a high water content, where a portion of the CO_2 dissolves in H_2O to form weakly acidic H_2CO_3, which subsequently reacts with minerals in the surrounding rock via dissolution.[12] Roof-floor strata develop small dissolution pores after 10 days of reaction, and these pores gradually expand or even open.[31]

The CO_2 injection duration during the implementation of CO_2-ECBM technology not only influences the single-well production of CBM but also controls the quantity of CO_2 injected and entrained.[23] This is related to "the expansion and deflection of the coal matrix surrounding the initial cracking during CO_2 infusion and the internal and large pores of the coal matrix expanding and deforming with increased permeability as the CO_2 infusion amount continues to rise".[9] The alterations in coal petrography performance due to CO_2 injection are time-dependent and phasic.[18] It is demonstrated that the maximum reduction in the elastic modulus and peak strength of the coal petrography can reach 30%−69% 3 days prior to CO_2 injection.[80] Over a short time frame, nonuniform expansion and deformations, as well as additional expansion stress within the coal petrography, cause CO_2 transport in the coal seam to be dominated by Darcy seepage.[81] In contrast, under long-term interactions, mineral erosion, loss of macromolecules, and Fick diffusion prevail in CO_2 transport in coal.[82] Consequently, a suitable coal-bearing formation can retain CO_2 for 100 a or even over 1000 a.[21]

5. FEASIBILITY EVALUATION OF CO_2 STORAGE IN COAL SEAMS

Previous studies have conducted geological site selection and environmental risk assessment for CO_2 sequestration through an analytic hierarchy process, gray correlation method, analytic hierarchy process fuzzy index method, fuzzy comprehensive evaluation method, and numerical simulation method.[24,82−84] However, there is still a lack of effective, systematic, and accurate evaluation methods for the feasibility of CO_2 geological sequestration in coal seams.[79] Therefore, the feasibility evaluation of CO_2 geological sequestration in coal seams is proposed in this paper (Figure 5).

Initially, the survey of coal field geological conditions necessitates understanding geological factors such as coal quality, structural background, hydrological conditions, reservoir physical properties, coal seams, and surrounding rocks in the study area.

Subsequently, geological storage of CO_2 in coal seams should adhere to principles of site selection feasibility, injection controllability, sequestration security, and development economy. Site selection feasibility serves as the foundation for

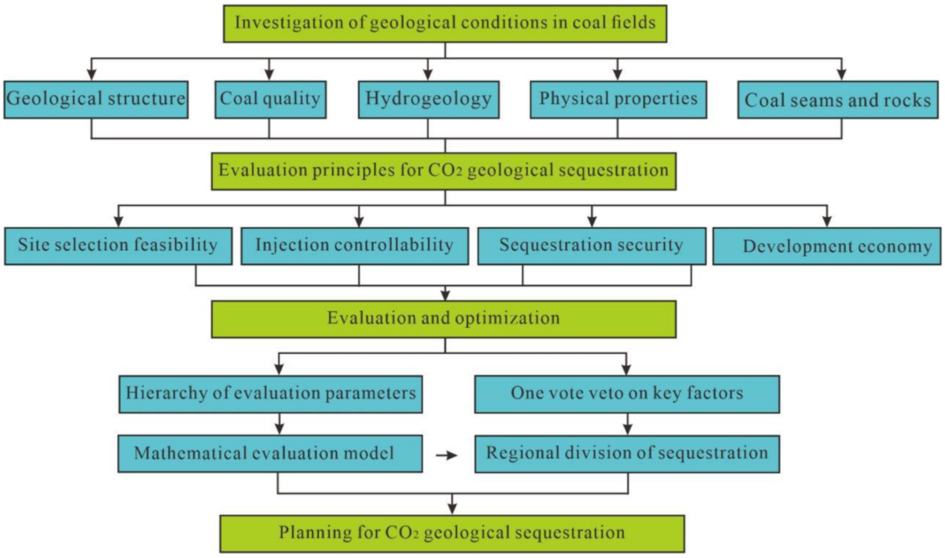


Figure 5. Geological evaluation and optimization process for CO_2 geological sequestration in coal seams.

geological storage of CO_2 in coal seams.[85] Injection controllability represents a decisive indicator of CO_2 storage in coal seams and is influenced by reservoir physical properties like coal seam porosity, permeability, and breakthrough pressure resistance.[6,17] The security of sequestration and development economy are prerequisites and guarantee conditions for geological storage of CO_2 in coal seams.[22,26] Sequestration security encompasses the entire process from preconstruction site selection to several years post CO_2 storage.[85,86] Development economy is jointly governed by geological factors such as coal rank, physical properties, effective thickness, geological structure, and engineering factors like CO_2 injection and production increase.[29−31] Also, it must be well recognized that CO_2 leaks directly or indirectly threaten the stability of the lithosphere, hydrosphere, biosphere, and atmospheric ecosystems.

Finally, the evaluation and optimization of CO_2 sequestration potential in coal seams involve clarifying the hierarchy of evaluation parameters, identifying the primary and secondary factors affecting CO_2 storage in coal seams, establishing a mathematical evaluation model based on the comparison, evaluation, and assignment of evaluation parameters. This process should be combined with the study area's actual situation, existing geological data, and related research results to organize the evaluation parameters and classify the CO_2 storage potential area into various favorable and unfavorable areas based on numerical values. Simultaneously, attention should be paid to enhancing the "one-vote veto" power of CO_2 storage to rapidly identify unsuitable areas for coal seam storage in mining regions, further analyze the geological storage approaches for CO_2 in coal seams, and propose recommendations for CO_2 geological storage plans and rational layout.

6. CONCLUSIONS

1. Optimal coal seams for geological sequestration of CO_2 should possess burial depths of 300−1300 m, permeability exceeding 0.01×10^{-3} μm^2, roof-floor strata with water isolation toughness, and high-rank bituminous coal or anthracite with low ash yield. It is essential to avoid areas with complex geological structures, shallow freshwater layers, and intricate hydrological conditions.
2. The feasibility evaluation of CO_2 geological sequestration in coal seams relies on a comprehensive understanding of geological factors within the coal field. This includes integrating the evaluation principles of site selection feasibility, injection controllability, sequestration security, and development economy, utilizing a range of mathematical models and employing the "one-vote veto" power to optimize the storage area and provide suggestions for a rational layout of CO_2 geological sequestration.

■ AUTHOR INFORMATION

Corresponding Authors

Meng Wu − *Jiangsu Mineral Resources and Geological Design and Research Institute, China National Administration of Coal Geology, Xuzhou, Jiangsu 221006, China; Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process, Ministry of Education, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China;* orcid.org/0000-0001-7715-9368;
Email: mwu476452783@126.com

Yong Qin − *Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process, Ministry of Education, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China;* orcid.org/0000-0002-7478-8828;
Email: yongqin@cumt.edu.cn

Authors

Yuanyuan Zhang − *Jiangsu Mineral Resources and Geological Design and Research Institute, China National Administration of Coal Geology, Xuzhou, Jiangsu 221006, China*

Shifei Zhu − *Jiangsu Mineral Resources and Geological Design and Research Institute, China National Administration of Coal Geology, Xuzhou, Jiangsu 221006, China*

Guchun Zhang − *Jiangsu Mineral Resources and Geological Design and Research Institute, China National Administration of Coal Geology, Xuzhou, Jiangsu 221006, China*

Fengjuan Lan − *Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process, Ministry of Education, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China*
Xuejuan Song − *School of Civil Engineering, Xuzhou University of Technology, Xuzhou, Jiangsu 221018, China*
Lele Feng − *School of Safety and Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China*; orcid.org/0000-0001-5090-5295
Yunhu Qin − *Jiangsu Mineral Resources and Geological Design and Research Institute, China National Administration of Coal Geology, Xuzhou, Jiangsu 221006, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c01148

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by the Science and Technology Projects in Xinjiang Autonomous Region (2022B01012-3), the Key Social Development Project of Xuzhou Science and Technology Bureau (KC21147), the Open Fund of Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process of the Ministry of Education (China University of Mining and Technology) (2022-006), and the Special Science and Technology Fund of China National Administration of Coal Geology (ZMKJ-2019-J13).

■ REFERENCES

(1) Fourier, J. B. On the temperatures of the terrestrial sphere and interplanetary space. *Mémoires de l'Académie Royale des Sciences* **1827**, *7*, 569−603.

(2) Tyndall, J. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction. *Philos. Mag.* **1861**, *22*, 169−194.

(3) Wang, R.; Wang, Q.; Niu, Q.; Pan, J.; Wang, H.; Wang, Z. CO_2 adsorption and swelling of coal under constrained conditions and their stage-change relationship. *J. Nat. Gas. Sci. Eng.* **2020**, *76*, 103205.

(4) Davis, S. J.; Caldeira, K.; Matthews, H. D. Future CO_2 emissions and climate change from existing energy infrastructure. *Science* **2010**, *329* (5997), 1330−1333.

(5) He, X.; Wang, A.; Dou, L.; Song, D.; Zu, Z.; Li, Z. Technology of microseismic dynamic monitoring on coal and gas outburst-prone zone. *J. China Coal Soc.* **2018**, *43* (11), 3122−3129.

(6) Hasselmann, K.; Latif, M.; Hooss, G.; Azar, C.; Edenhofer, O.; Jaeger, C. C.; Johannessen, O. M.; Kemfert, C.; Welp, M.; Wokaun, A. The challenge of long term climate change. *Science* **2003**, *302* (5652), 1923−1925.

(7) Shi, Q.; Cui, S.; Wang, S.; Mi, Y.; Sun, Q.; Wang, S.; Shi, C.; Yu, J. Experiment study on CO_2 adsorption performance of thermal treated coal: Inspiration for CO_2 storage after underground coal thermal treatment. *Energy* **2022**, *254*, 124392.

(8) Han, S. *CO_2 Containment mechanism in deep anthracite related to CO_2-ECBM and assessment methodology for CO_2 storage capacity*; Xuzhou, China University of Mining and Technology. 2020.

(9) Qu, H.; Liu, J.; Chen, Z.; Wang, J.; Pan, Z.; Connell, L.; Elsworth, D. Complex evolution of coal permeability during CO_2 injection under variable temperatures. *Int. J. Greenh. Gas Con.* **2012**, *9*, 281−293.

(10) Qin, Y.; Shen, J.; Shi, R. Strategic value and choice on construction of large CMG industry in China. *J. China Coal Soc.* **2022**, *47* (1), 371−387.

(11) Connell, L. D.; Lu, M.; Pan, Z. J. An analytical coal permeability model for triaxial strain and stress conditions. *Int. J. Coal Geol.* **2010**, *84* (2), 103−114.

(12) Zou, Y.; Li, S.; Ma, X.; Zhang, S.; Li, N.; Chen, M. Effects of CO_2-brine-rock interaction on porosity/permeability and mechanical properties during supercritical-CO_2 fracturing in shale reservoirs. *J. Nat. Gas. Sci. Eng.* **2018**, *49*, 157−168.

(13) Han, S.; Sang, S.; Liang, J.; Zhang, J. Supercritical CO_2 adsorption in a simulated deep coal reservoir environment, implications for geological storage of CO_2 in deep coals in the southern Qinshui Basin, China. *Energy Sci. Eng.* **2019**, *7* (2), 488−503.

(14) Luo, Z.; Fang, M.; Li, M. Carbon dioxide capture, storage and utilization technology. *Beijing: China Electric Power Press* **2012**, 261−279.

(15) Gensterblum, Y.; Busch, A.; Krooss, B. M. Molecular concept and experimental evidence of competitive adsorption of H_2O, CO_2 and CH_4 on organic material. *Fuel* **2014**, *115*, 581−588.

(16) Fathi, E.; Akkutlu, I. Y. Multi-component gas transport and adsorption effects during CO_2 injection and enhanced shale gas recovery. *Int. J. Coal Geol.* **2014**, *123* (2), 52−61.

(17) Jiang, W.; Cui, Y.; Zhang, Q.; Li, Y. H. The quantum chemical study on the coal surface interacting with CH_4 and CO_2. *J. China Coal Soc.* **2006**, *31* (2), 237−240.

(18) Sang, S.; Niu, Q.; Cao, L.; Wang, W. Mechanical response characteristic and mechanism of coal-rock with CO_2 injection in deep seam: A review. *Earth Sci.* **2022**, *47* (5), 1849−1864.

(19) He, X.; Tian, X.; Song, D. Progress and expectation of CO_2 sequestration safety in coal seams. *Coal Sci. Technol.* **2022**, *50* (1), 212−219.

(20) Li, Z. *Coal mine geology*, 2nd ed.; Coal Industry Press, 2013.

(21) Yao, S.; Tang, Z.; Tan, L.; Pei, W. The CO_2 geological sealing conditions and potential evaluation in coal seams in Jiangsu Province. *Geol. J. China Univ.* **2012**, *18* (2), 203−214.

(22) Shen, P.; Liao, X. *Geological burial of carbon dioxide and enhanced oil recovery technology*; Petroleum Industry Press: Beijing, 2009.

(23) Omotilewa, O. J.; Panja, P.; Vega-Ortiz, C.; McLennan, J. Evaluation of enhanced coalbed methane recovery and carbon dioxide sequestration potential in high volatile bituminous coal. *J. Nat. Gas Sci. Eng.* **2021**, *91*, 103979.

(24) Xu, Y. *Surrounding rock deformation and fracture developing numerical simulation study for underground coal gasification couping carbon dioxide storage*; China University of Mining and Technology: Xuzhou, 2020.

(25) Wu, M.; Qin, Y.; Li, G.; Shen, J.; Song, X.; Zhu, S.; Han, L. Research progress on influencing factors and evaluation methods of underground coal gasification. *Coal Sci. Technol.* **2022**, *50* (8), 259−269.

(26) Godec, M.; Koperna, G.; Gale, J. CO_2-ECBM: A review of its status and global potential. *Energy Procedia* **2014**, *63*, 5858−5869.

(27) Pan, Z.; Ye, J.; Zhou, F.; Tan, Y.; Connell, L. D.; Fan, J. CO_2 storage in coal to enhance coalbed methane recovery: a review of field experiments in China. *Int. Geol. Rev.* **2018**, *60* (5−6), 754−776.

(28) Xie, X.; Economides, M. J. The impact of carbon geological sequestration. *J. Nat. Gas Sci. Eng.* **2009**, *1* (3), 103−111.

(29) White, C. M.; Smith, D. H.; Jones, K. L.; Goodman, A. L.; Jikich, S. A.; LaCount, R. B.; DuBose, S. B.; Ozdemir, E.; Morsi, B. I.; Schroeder, K. T. Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery-A review. *Energy Fuels* **2005**, *19* (3), 659−724.

(30) Sun, Y.; Zhou, L.; Huo, F. Water characteristics of Majiagou formation Ma51 submember in Ordos Basin and the significance for CO2 geological sequestration. *J. Earth Environ.* **2019**, *10* (1), 49−57.

(31) Wang, F.; Yao, Y.; Wen, Z.; Sun, Q.; Yuan, X. Effect of water occurrences on methane adsorption capacity of coal: A comparison between bituminous coal and anthracite coal. *Fuel* **2020**, *266*, 117102.

(32) Lemieux, J. M. Review: The potential impact of underground geological storage of carbon dioxide in deep saline aquifers on shallow groundwater resources. *Hydrogeol. J.* **2011**, *19* (4), 757−778.

(33) Tian, X.; Cheng, L.; Cao, R.; Zhang, M.; Guo, Q.; Wang, Y.; Zhang, J.; Cui, Y. Potential evaluation of CO2 storage and enhanced oil recovery of tight oil reservoir in the Ordos Basin, China. *J. Environ. Biol.* **2015**, *36*, 789−797.

(34) Chowdhury, S.; Rakesh, M.; Medhi, S.; Trivedi, J.; Sangwai, J. S. Pore-scale flow simulation of supercritical CO_2 and oil flow for simultaneous CO_2 geo-sequestration and enhanced oil recovery. *Environ. Sci. Pollut. Res. Int.* **2022**, *29* (50), 76003−76025.

(35) Watson, M. N.; Zwingmann, N.; Lemon, N. M. The Ladbroke grove-katnook carbon dioxide natural laboratory: A recent CO_2 accumulation in a lithic sandstone reservoir. *Energy* **2004**, *29* (9), 1457−1466.

(36) Xu, T.; Apps, J. A.; Pruess, K. Mineral sequestration of carbon dioxide in a sandstone-shale system. *Chem. Geol.* **2005**, *217* (3−4), 295−318.

(37) Jiang, W.; Cui, Y. A discussion on main geologic controlling factors of CO_2 sequestration in deep coal seams. *Coal Geol. China* **2010**, *22* (11), 1−6.

(38) Li, L.; Zhao, N.; Wei, W.; Sun, Y. A review of research progress on CO_2 capture, storage, and utilization in Chinese Academy of Sciences. *Fuel* **2013**, *108*, 112−130.

(39) Wen, H.; Hao, J.; Ma, L.; Zheng, X. Experimental study on replacing coal seam CH_4 with CO_2 gas. *ACS Omega* **2022**, *7* (1), 1395−1403.

(40) Sampath, K.H.S.M.; Perera, M.S.A.; Matthai, S.K.; Ranjith, P.G.; Dong-yin, L. Modelling of fully-coupled CO_2 diffusion and adsorption-induced coal matrix swelling. *Fuel* **2020**, *262*, 116486.

(41) Ni, X.; Li, Q.; Wang, Y.; Gao, S. Permeability variation characteristics of coal after injecting carbon dioxide into a coal seam. *Int. J. Min. Sci. Technol.* **2015**, *25* (4), 665−670.

(42) Jeddizahed, J.; Rostami, B. Experimental investigation of injectivity alteration due to salt precipitation during CO2 sequestration in saline aquifers. *Adv. Water Resour.* **2016**, *96*, 23−33.

(43) Moore, T. A. Coalbed methane: A review. *Int. J. Coal Geol.* **2012**, *101* (1), 36−81.

(44) Yan, J.; Meng, Z.; Zhang, K.; Yao, H.; Hao, H. Pore distribution characteristics of various rank coals matrix and their influences on gas adsorption. *J. Pet. Sci. Eng.* **2020**, *189*, 107041.

(45) Mukherjee, M.; Misra, S. A review of experimental research on Enhanced Coal Bed Methane (ECBM) recovery via CO_2 sequestration. *Earth Sci. Rev.* **2018**, *179*, 392−410.

(46) Merkel, A.; Gensterblum, Y.; Krooss, B. M.; Amann, A. Competitive sorption of CH_4, CO_2 and H_2O on natural coals of different rank. *Int. J. Coal Geol.* **2015**, *150−151*, 181−192.

(47) Jenkins, C. R.; Cook, P. J.; Ennis-King, J.; Undershultz, J.; Boreham, C.; Dance, T.; de Caritat, P.; Etheridge, D. M.; Freifeld, B. M.; Hortle, A.; Kirste, D.; Paterson, L.; Pevzner, R.; Schacht, U.; Sharma, S.; Stalker, L.; Urosevic, M. Safe storage and effective monitoring of CO_2 in depleted gas fields. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109* (2), 35−41.

(48) Liang, W.; Zhang, B.; He, W.; Yao, H. Experimental research on supercritical CO_2 enhanced coalbed methane recovery in different rank coals. *J. China Coal Soc.* **2020**, *45* (1), 197−203.

(49) Nie, B.; Liu, X.; Yang, L.; Meng, J.; Li, X. Pore structure characterization of different rank coals using gas adsorption and scanning electron microscopy. *Fuel* **2015**, *158*, 908−917.

(50) Zhang, B. *Investigation of Supercritical CO_2 Flow Behavior and Mechanical Deformation in Different Rank Coals*; Taiyuan University of technology: Taiyuan, 2019.

(51) He, W.; Liang, W.; Zhang, B.; Li, Z. Experimental study on swelling characteristics of CO_2 adsorption and storage in different coal rank. *J. China Coal Soc.* **2018**, *43* (5), 1408−1415.

(52) Chen, Y.; Tang, D.; Xu, H.; Tao, S.; Li, S.; Yang, G.; Yu, J. Pore and fracture characteristics of different rank coals in the eastern margin of the Ordos Basin, China. *J. Nat. Gas Sci. Eng.* **2015**, *26*, 1264−1277.

(53) Ranathunga, A. S.; Perera, M. S. A.; Ranjith, P. G. Influence of CO_2 adsorption on the strength and elastic modulus of low rank Australian coal under confining pressure. *Int. J. Coal Geol.* **2016**, *167*, 148−156.

(54) Day, S.; Sakurovs, R.; Weir, S. Supercritical gas sorption on moist coals. *Int. J. Coal Geol.* **2008**, *74* (3), 203−214.

(55) Siemons, N.; Busch, A. Measurement and interpretation of supercritical CO_2 sorption on various coals. *Int. J. Coal Geol.* **2007**, *69* (4), 229−242.

(56) Liu, J. F.; Peach, C. J.; Spiers, C. J. Anisotropic swelling behaviour of coal matrix cubes exposed to water vapour: Effects of relative humidity and sample size. *Int. J. Coal Geol.* **2016**, *167*, 119−135.

(57) Du, Y.; Fu, C. Q.; Pan, Z. J.; Sang, S.; Wang, W.; Liu, S.; Zhao, Y.; Zhang, J. Geochemistry effects of supercritical CO_2 and H_2O on the mesopore and macropore structures of high-rank coal from the Qinshui Basin, China. *Int. J. Coal Geol.* **2020**, *223*, 103467.

(58) Mastalerz, M.; Drobniak, A.; Walker, R.; Morse, D. Coal lithotypes before and after saturation with CO2: Insights from micro- and mesoporosity, fluidity, and functional group distribution. *Int. J. Coal Geol.* **2010**, *83* (4), 467−474.

(59) Liu, S.; Sang, S.; Ma, J.; Wang, T.; Du, Y.; Fang, H. Effects of supercritical CO_2 on micropores in bituminous and anthracite coal. *Fuel* **2019**, *242*, 96−108.

(60) Zhou, X.; Sang, S.; Niu, Q.; Zhang, K.; Liu, F.; Wang, W.; Chang, J. Changes of multiscale surface morphology and pore structure of mudstone associated with supercritical CO_2-water exposure at different times. *Energy Fuels* **2021**, *35* (5), 4212−4223.

(61) Soroush, M.; Wessel-Berg, D.; Torsaeter, O.; Kleppe, J. Investigating residual trapping in CO_2 storage in saline aquifers-application of a 2D glass model, and image analysis. *Energy Sci. Eng.* **2014**, *2* (3), 149−163.

(62) Masoudian, M. S.; Airey, D. W.; El-Zein, A. Experimental investigations on the effect of CO_2 on mechanics of coal. *Int. J. Coal Geol.* **2014**, *128*, 12−23.

(63) Zhang, G.; Ranjith, P.; Wu, B.; Perera, M. S. A.; Haque, A.; Li, D. Synchrotron X-ray tomographic characterization of microstructural evolution in coal due to supercritical CO_2 injection at in-situ conditions. *Fuel* **2019**, *255*, 115696.

(64) Luo, S.; Xu, R.; Jiang, P. Pore-scale numerical simulation on breakthrough pressure gradient during CO_2 geological storage. *J. Eng. Thermophys.* **2011**, *32* (5), 819−823.

(65) He, D.; Jiang, P.; Xu, R. Pore-scale experimental investigation of the effect of supercritical CO_2 injection rate and surface wettability on salt precipitation. *Environ. Sci. Technol.* **2019**, *53* (24), 14744−14751.

(66) Fan, C.; Li, S.; Luo, M.; Zhou, L.; Zhang, H.; Yang, Z. Effects of N and S functionalities on binary gases co-adsorption onto coal macromolecule. *Energy Fuels* **2019**, *33* (5), 3934−3946.

(67) Xiang, J.; Lei, L. Study on influence of coal surface functional groups on methane and carbon dioxide adsorption properties. *Coal Sci. Technol.* **2021**, *49* (6), 145−151.

(68) Yu, S.; Bo, J.; Fengjuan, L. Competitive adsorption of $CO_2/N_2/CH_4$ onto coal vitrinite macromolecular: Effects of electrostatic interactions and oxygen functionalities. *Fuel* **2019**, *235* (1), 23−38.

(69) Yu, S.; Bo, J.; Meijun, Q. Molecular dynamic simulation of self- and transport diffusion for $CO_2/CH_4/N_2$ in low-rank coal vitrinite. *Energy Fuels* **2018**, *32* (3), 3085−3096.

(70) Ozdemir, E. Chemistry of the adsorption of carbon dioxide by Argonne premium coals and a model to simulate CO_2 sequestration in coal seams. *Dissertation of Doctor of Philiosophy of University of Pittsburgh*, 2004.

(71) Wu, D.; Miao, F.; Sun, K.; Wang, T.; Zhai, W. Experimental study on permeability law of combined coal and rock. *J. Liaoning Technical. Univ. (Nat. Sci. Ed.)* **2020**, *39* (2), 113−118.

(72) Fan, J.; Wang, Y.; Wang, J. Influence of temperature on the replacement of CH_4 by supercritical CO_2. *Sci. Technol. Rev.* **2015**, *33* (24), 28−33.

(73) Sakurovs, R.; Day, S.; Weir, S.; Duffy, G. Temperature dependence of sorption of gases by coals and charcoals. *Int. J. Coal Geol.* **2008**, *73* (3−4), 250−258.

(74) Zhang, X.; Lu, Y.; Tang, J.; Zhou, Z.; Liao, Y. Experimental study on fracture initiation and propagation in shale using supercritical carbon dioxide fracturing. *Fuel* **2017**, *190*, 370−378.

(75) Zhang, J.; Sang, S.; Han, S.; Zhang, F.; Xu, A.; Liu, Q. CO_2 adsorption on anthracite with different moisture contents and its implication for CO_2 geological storage in deep coal. *Coal Geo. Explor.* **2022**, *50* (9), 96−103.

(76) Saurabh, S.; Harpalani, S. Anisotropy of coal at various scales and its variation with sorption. *Int. J. Coal Geol.* **2019**, *201*, 14−25.

(77) Li, Y.; Wang, J.; Wang, Z.; Pan, Z. Variation in Permeability during CO_2-CH_4 Displacement in Coal Seams. Part 2: Modeling and Simulation. *ACS Omega* **2020**, *5* (29), 18432−18440.

(78) Bachu, S. CO_2 storage in geological media: Role, means, status and barriers to deployment. *Prog. Energy Combust. Sci.* **2008**, *34* (2), 254−273.

(79) Bradshaw, J.; Bachu, S.; Bonijoly, D.; Burruss, R.; Holloway, S.; Christensen, N. P.; Mathiassen, O. M. CO_2 storage capacity estimation: Issues and development of standards. *Int. J. Greenh. Gas Con.* **2007**, *1* (1), 62−68.

(80) Qi, L.; Peng, X.; Wang, Z.; Lou, X. Study on reasonable adsorption equilibrium Time of anthracite based on COMSOL simulation. *Safety in Coal Mines* **2015**, *46* (3), 51−53.

(81) Li, W.; Pang, B.; Su, E.-l.; Yang, Q.; Liu, Q.; Cheng, Y. Time-dependence of mechanical property alterations on anthracite coals treated by supercritical carbon dioxide. *Geofluids* **2019**, *2019*, 1−9.

(82) Wu, Y.; Li, Y.; Fang, Q.; Li, S. Potentiality and suitability assessment of the CO_2 geological storage of sedimentary basins in South China. *Safety Environ. Eng.* **2014**, *21* (5), 64−70.

(83) Mi, Z.; Wang, F.; Yang, Y.; Wang, F.; Hu, T.; Tian, H. Evaluation of the potentiality and suitability for CO2 geological storage in the Junggar Basin, northwestern China. *Int. J. Greenh. Gas Con.* **2018**, *78*, 62−72.

(84) Ali, M.; Jha, N. K.; Pal, N.; Keshavarz, A.; Hoteit, H.; Sarmadivaleh, M. Recent advances in carbon dioxide geological storage, experimental procedures, influencing parameters, and future outlook. *Earth Sci. Rev.* **2022**, *225*, 103895.

(85) Hosseini, M.; Fahimpour, J.; Ali, M.; Keshavarz, A.; Iglauer, S. Capillary sealing efficiency analysis of caprocks: Implication for hydrogen geological storage. *Energy Fuels* **2022**, *36* (7), 4065−4075.

(86) Fleury, M.; Pironon, J.; Le Nindre, Y.M.; Bildstein, O.; Berne, P.; Lagneau, V.; Broseta, D.; Pichery, T.; Fillacier, S.; Lescanne, M.; Vidal, O. Evaluating sealing efficiency of caprocks for CO2 storage: An overview of the geocarbone integrity program and results. *Energy Procedia* **2011**, *4*, 5227−5234.