International Journal of Coal Science & Technology (2025) 12:18
https://doi.org/10.1007/s40789-025-00750-z

RESEARCH

CO_2 storage capacity of coal seams: a screening and geological review of carboniferous coal formations of Kazakhstan

Mohammad Asif[1,2] · **Medet Junussov**[2] · **Sotirios Longinos**[2] · **Randy Hazlett**[2] · **Sandugash Satibekova**[3]

Received: 13 October 2023 / Revised: 9 March 2024 / Accepted: 6 January 2025

Abstract

The increasing atmospheric CO_2 concentration linked to human activity results in global warming by the greenhouse effect. This anthropogenic CO_2 may be sequestrated into geological formations, e.g., porous basalts, saline aquifers, depleted oil or gas reservoirs, and unmineable coal seams. Furthermore, carbon capture, utilization, and storage (CCUS) methods are an acceptable and sustainable technology to meet the goals of the Paris Agreement, in which Kazakhstan is expected to reduce greenhouse gas emissions by 25% compared with the 1990 level. Unmineable coal seams are an attractive option among all geostorage solutions, as CO_2 sequestration in coal comes with an income stream via enhanced coalbed methane (ECBM) recovery. This paper identifies four carboniferous coal formations, namely Karagandy, Teniz-Korzhinkol, Ekibustuz, and Chu coal basins of Kazakhstan, as CO_2 geostorage solutions for their unmineable coal seams. The ideal depth of CO_2 storage is identified as 800 m to ensure the supercritical state of CO_2. However, the Ekibustuz coal basin fails to meet the required depth of 800 m in its unmineable coal seams. The conventional formula for calculating CO_2 storage in coal basins has been modified, and a new formula has been proposed for assessing the CO_2 storage potential in a coal seam. The CO_2 storage capacities of unmineable coal seam of these coal basins are 24.60 Bt, 0.61 Bt, 14.02 Bt, and 5.42 Bt, respectively. The Langmuir volume of the coal fields was calculated using the proximate analysis of coalfields and found to vary between 36.42 and 98.90 m^3/ton. This paper is the first to outline CO_2 storage potential in Kazakhstani coal basins, albeit with limited data, along with a detailed geological and paleographic review of the carboniferous coalfields of Kazakhstan. A short overview of the CO_2-ECBM process was also included in the paper. Instead of any experimental work for CO_2 storage, this paper attempts to present the CO_2 storage capacity of carboniferous coal formation using the modified version of previously determined formulas for CO_2 storage.

Keywords Coal basins · Kazakhstan · CO_2 storage · ECBM recovery · Greenhouse gas · Global warming

Abbreviations

D_{max}, m	Maximum depth of coal seam
A_T, km^2	Total area of the reservoir
T_c, m	Thickness of the coal seam
N	Number of coal seams
T_r, Billion tonnes (Bt)	Total reserve
A, % air dry basis (adb)	Ash content
M, % air dry basis (adb)	Moisture content
C, % air dry basis (adb)	Carbon content
A_c, km^2	Area of the coal seam
ρ_c, g/cc	Density of coal
E_f	Storage efficiency of coal
V_{CO_2}, m^3/t	Adsorption capacity of coal with respect to CO_2
ρ_g, cc/g	Density of CO_2 at different depth
S_t, Bt	CO_2 storage capacity
S_{th}, t	Theoretical CO_2 geological storage capacity
S_{eff}, t	Effective CO_2 geological storage capacity

✉ Mohammad Asif
masifkhan92@gmail.com

✉ Medet Junussov
medet.junussov@nu.edu.kz

✉ Sotirios Longinos
s.n.longinos@gmail.com

[1] Department of Geotechnical Engineering, Tongji University, Shanghai, China

[2] School of Mining and Geosciences, Nazarbayev University, Astana, Kazakhstan

[3] Satbayev University, Almaty, Kazakhstan

ρ_{CO_2}, kg/m^3	CO_2 density at standard condition (1.977 kg/m^3)
n_{ab}, m^3/t	Absolute CO_2 adsorption capacity
n_f, m^3/t	Free CO_2 adsorption capacity
n_s, m^3/t	CO_2 dissolution storage capacity
G, m^3	Volumetric gas resource in residual coal
RF, %	Recovery factor methane enhanced by CO_2 injection
ER	Replacement ratio of CH_4 to CO_2
R_r	Residual coal reserve
G_c, m^3/t	Gas content in residual coal
$V_{(CO_2)_F}$, m^3	Volume of CO_2 that can be filled
A_m, m^2	Mined-out area,
s	Subsidence factor
TCGSC	Theoretical CO_2 geological storage capacity
ECGSC	Effective CO_2 geological storage capacity

1 Introduction

The growth in science, technology, and productivity during the industrial age of the nineteenth century was concurrent with wealth generation based upon cheap energy from fossil fuels and primarily coal (Asif et al. 2019c). This growth and the subsequent shift to petroleum for energy have also carried many challenges for human beings (Longinos et al. 2022, 2021). Anthropogenic climate change, or change in long-term climate patterns induced by human activity, is the greatest challenge facing us in the wake of this development (Asif et al. 2018a, b). Particularly, global warming, or the rise in average temperatures in the earth's atmosphere, is a critical phenomenon that is impacting and will continue to affect our planet in the foreseeable future (Longinos and Parlaktuna 2021). Global warming results from an accumulation of certain gases, e.g., CH_4 and CO_2, accumulating in the atmosphere beyond the natural balance in the carbon cycle. These gases trap the heat radiating from the earth that was generated from incident sunlight, thus increasing the average temperature of the earth's atmosphere. Since temperature plays a critical role in weather patterns, agriculture, and the security of economic systems, it is necessary to control the problem of human-induced global warming (Asif et al. 2022c; Serikov et al. 2022). According to the Intergovernmental Panel on Climate Change (IPCC), Global warming has caused the temperature to rise 1 °C above pre-industrial levels and may increase to 1.5 °C between 2030 and 2052 (IPCC 2018). The United Nations also commissioned a report in 2019 with a clear warning that the current rate of temperature rise will take a huge toll on lives, natural systems, and the economy (United Nations 2019).

The proposed goal to remove 1000 Giga tons of CO_2 from the earth's atmosphere by 2100 demands additional carbon dioxide removal (CDR) techniques and air capture plants. About 53 Giga tons of greenhouse gases are emitted each year, and the world would need to deploy enough CDRs to counteract more than 18 years of total global carbon emissions, as suggested by World Bank in 2016 (WBG 2016). The emission of CO_2 in the atmosphere has been increased to 130 ppm (280 to 410 ppm) from the preindustrial period to the present time (IPCC 2018). Five methods are suggested to counter the increasing emission of CO_2 in the atmosphere, e.g., switching to low-carbon generation fuel, increasing conservation, deploying energy efficient methods, improving environmental protection, and sequestering CO_2 (Meer 2005).

The sequestration of CO_2 in geological formations is presently the most feasible and effective method. Geological formations, e.g., the porous basalts, saline aquifers, depleted oil and gas reservoirs, or unmineable coal seams offer viable options for the longtime storage of CO_2 (Bachu and Adams 2003). A schematic diagram for the geological storage options of CO_2 has been shown in Fig. 1.

This paper provides a detailed geological review of the carboniferous coal basins of Kazakhstan and assesses their viability for CO_2 storage. The paper is divided into four parts: (1) A description of the energy sector using coal in Kazakhstan, (2) A short review of CO_2-ECBM recovery, (3) A detailed geological review of carboniferous coal basins in Kazakhstan, and (4) An assessment of Kazakhstan coal basins as for potential CO_2 storage.

2 Coal use and CO_2 emissions in Kazakhstan

Coal has experienced significant growth as a cheap and available energy source worldwide, surpassing the growth rates of gas, oil, nuclear, hydro, and other renewable sources (Muhammed et al. 2022). Similarly, in Kazakhstan, a country with a thriving economy, coal deposits play a vital role in meeting its energy demands. Additionally, Kazakhstan stands out for its extensive use of coal for household heating, ranking among the highest in the world. According to a report by The World-Watch Institute in 2020, Kazakhstan's carbon emissions amounted to approximately 272 million tons in 2019. Of these emissions, 235.3 million tons were attributed to energy-related activities, accounting for 0.55% of global emissions in terms of CO_2 equivalent. The sources

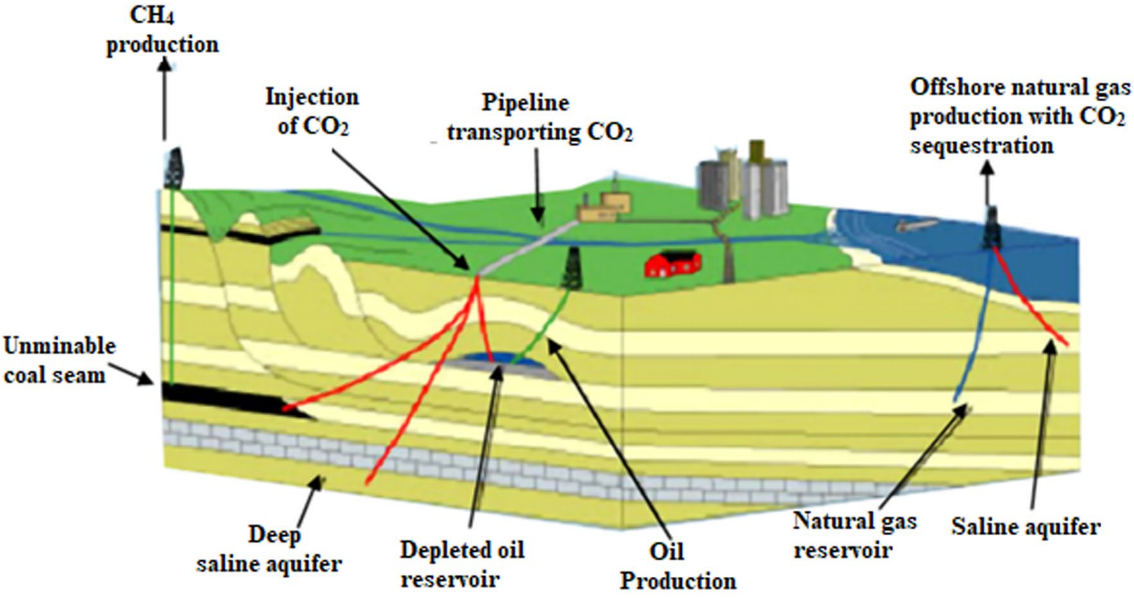


Fig. 1 Geologic storage options for carbon dioxide (Perera 2014)

of CO_2 emissions in Kazakhstan include fossil fuel combustion in various sectors, e.g., power generation industries, heating in residential complexes, and fuel for vehicles. Notably, coal-fired plants were responsible for an estimated 176 million tons of CO_2 emissions in 2019, comprising 70% of the country's annual emissions (Khoyashov et al. 2024). This high percentage can be attributed to the dominant use of coal as a fuel for power generation, contributing to over 70% of Kazakhstan's electricity production in 2022 (Agency 2022).

Kazakhstan, like many other countries, must prioritize the precise monitoring and regulation of methane emissions originating from coal mines, as stated in the ESR Report of 2022. The country faces additional environmental challenges due to its outdated, inefficient, and highly polluting coal-fired thermal power plants, as highlighted in the same report. With a total of 14 major coal-fired thermal power plants, Kazakhstan's concentration of these facilities is primarily found in its northern power zones, where coal production takes place, as illustrated in Fig. 2. The energy transition in Kazakhstan will be challenging.

3 CO_2-ECBM process: an overview

In coal mining, methane poses a risk to the health and safety of workers and operations. While the energy released in burning coal drives its use as a fuel, coal also contains large volumes of adsorbed methane – an energy transition low carbon generation fuel. While coal has this natural affinity to store methane, it has an even stronger affinity for CO_2, presenting a unique opportunity to sequester CO_2, usually a pure operational cost, while providing a low carbon generation fuel as an income stream (Baines and Worden 2004; Tiyntayev et al. 2022). The process is named CO_2-ECBM, where ECBM stands for Enhanced Coal Bed Methane (Asif et al. 2021).

Unmineable coal seams have advantages over geo-sequestration methods, as they are economically attractive and efficient for the environment. Concurrent with CO_2 injection, the preferential adsorption of CO_2 over CH_4 in coal displaces the methane rapidly (Ahuja et al. 2021). The CO_2-ECBM process is illustrated in Fig. 3a. The CO_2-ECBM process offers a dual advantage for humans as CO_2 can be permanently stored in the coalfields while enhancing the coalbed methane recovery. Furthermore, it was identified that ~ 98% of CO_2 could remain in the coal in an adsorbed form (Asif et al. 2019b, 2017; Bustin and Clarkson 1998). The initial commercial ECBM field and the longest trial were performed between 1995–2001 at the Allison unit in San Juan, where approximately 5 billion cubic feet were injected, resulting in a profit of $2 per thousand cubic feet. Other than this pilot project, significant projects have been conducted such as Powder River has been conducted e.g., Powder River Basin, Black Warrior Basin, Fenn-Big Valley in Alberta, Canada, the Yuabri project in Hokkaido, Japan, and China (including the Qinshui Basin from 2004 to 2015 and the APP ECBM project from 2011 to 2012) (Fan et al. 2023; Godec et al. 2014).

The work of a few researchers relevant to the CO_2-ECBM recovery has been summarized from Tables 1, 2 and 3 from the start of the research in 1998 till date (2024).

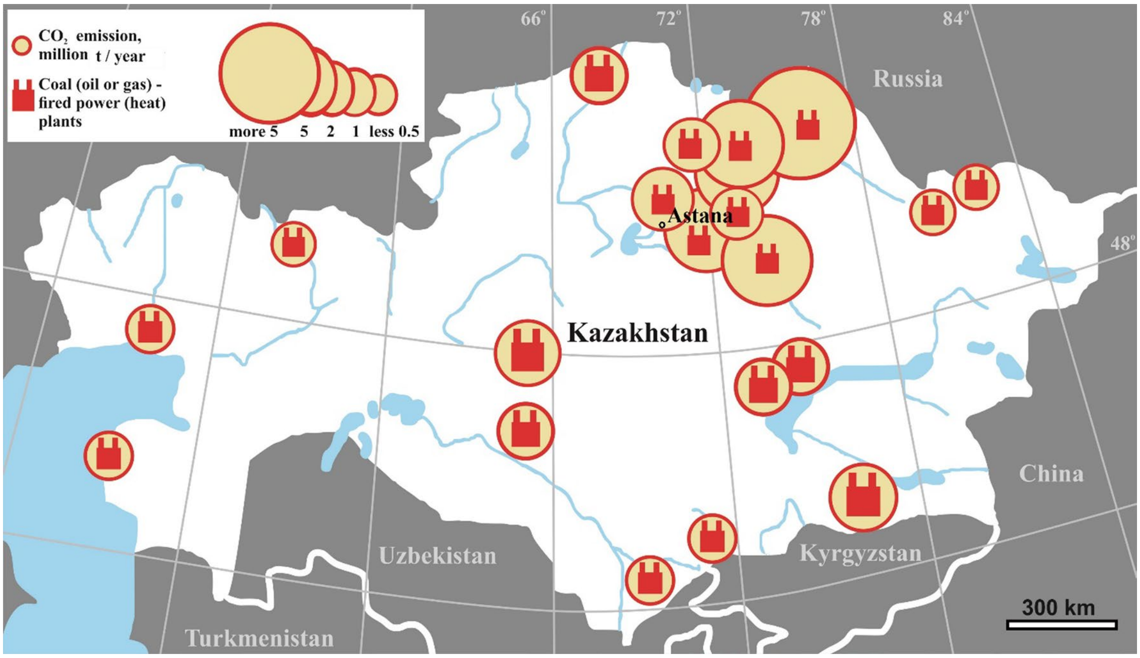


Fig. 2 Significant emission sources of CO_2 and the energy operations of coal-fired, oil-fired, or gas-fired power and heating plants (modified after Abuov et al. 2020; National inventory report 2016))

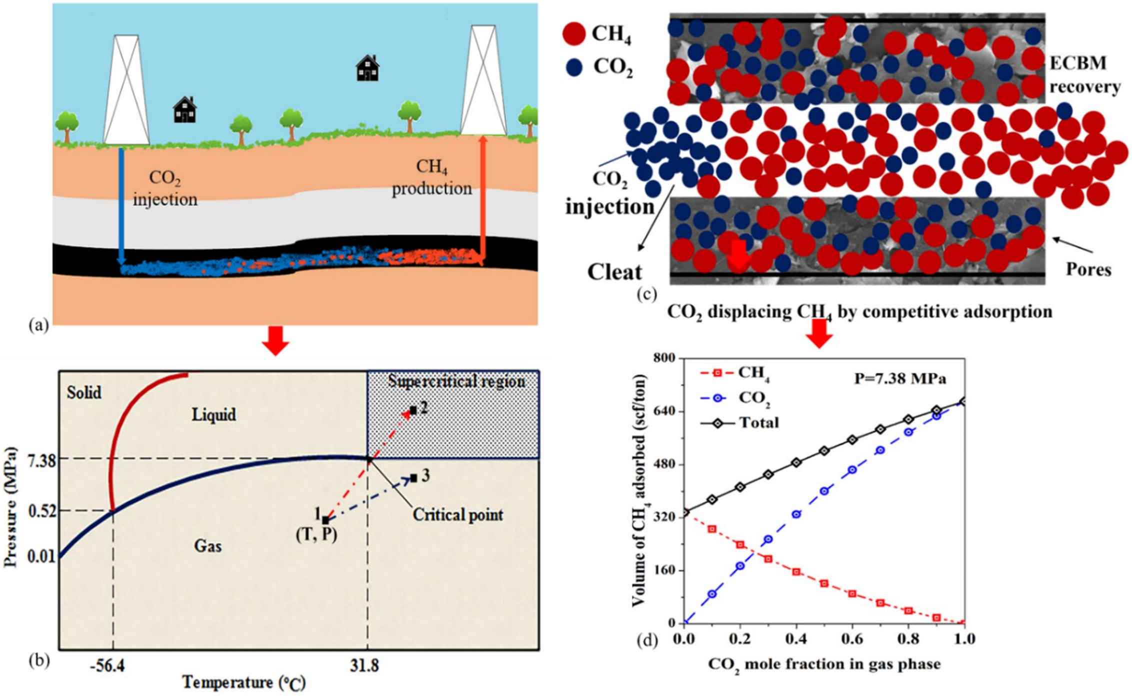


Fig. 3 Depiction of mechanism in CO_2-ECBM process (Asif et al. 2022c)

Table 1 includes theoretical and modeling research and Table 2 includes some of the experimental research in the CO_2-ECBM process. The pilot test and commercial projects have been included in Table 3.

The mechanism of the CO_2-ECBM process lies in the adsorption phenomenon itself. When CH_4 or CO_2 interacts with coal, there is physisorption rather than chemisorption. Thus, this process alters the adsorption energy and

Table 1 CO_2-ECBM review: theoretical and modeling research

S.N	Title of paper	Significance	References
1	"Enhanced Coalbed Methane using CO_2 injection: Worldwide resource and CO_2 sequestration potential"	This study was the first to describe reservoir engineering principles for ECBM recovery using CO_2 sequestration	Stevens et al. (1998)
2	"Reservoir Engineering Aspects of CO_2 Sequestration in Coals"	This was the first paper to modify Katz and Tek's objectives from natural gas for utilizing these techniques for CO_2 sequestration	Seidle (2000)
3	"Numerical Simulator Comparison Study for Enhanced Coalbed Methane Recovery Processes, Part I: Pure Carbon Dioxide Injection"	This research was about the comparison of results of different numerical simulators for ECBM recovery	Law et al. (2002)
4	"Sequestration of Carbon Dioxide in Coal with Enhanced Coalbed Methane Recovery: A Review"	A detailed review on CO_2 sequestration and ECBM recovery with a particular focus on reservoir properties, a field test in U.S. coalbeds, the economics involved in ECBM recovery and health and safety, etc	White et al. (2005)
5	"A Case Study on the Numerical Simulation of Enhanced Coalbed Methane Recovery"	This paper uses a hypothetical pilot-scale project to define the sorption and diffusion characteristics of coal for CO_2 sequestration	Wei et al. (2006)
6	"A Review on Recent Advances in the Numerical Simulation for Coalbed Methane Recovery Process"	This paper points out the limitations of existing CBM models with a particular focus on ECBM recovery	Wei et al. (2007)
7	"Modelling of Mixed-Gas Adsorption and Diffusion in Coalbed Reservoirs"	This paper shows missed-gas adsorption and diffusion modeling in coalbeds using a reservoir simulation study of the Yubari CO_2 storage project	Shi and Durucan (2008)
8	"Enhanced Coalbed Methane Recovery"	This paper provides the feasibility of ECBM recovery using a summary of the results of existing ECBM field tests	Mazzotti et al. (2009)
9	"CO_2 sequestration in coals and enhanced coalbed methane recovery: New numerical approach"	A dynamic multicomponent transport (DMCT) model was applied in this paper to simulate gas diffusion and flow behavior of mixed gases ECBM recovery	Wei et al. (2010)
10	"Adsorption and strain: The CO2-induced swelling of coal"	The theoretical framework was developed to define sorption-induced strain in a porous solid. This paper presents that injection of CO_2 for the ECBM process caused coal matrix swelling and decreased permeability of coal	Vandamme et al. (2010)
11	" A model for enhanced coal bed methane recovery aimed at carbon dioxide storage"	One dimensional mathematical model was used to judge the performance of enhanced coalbed methane recovery using CO_2 sequestration	Pini et al. (2011)
12	"Implementing Simulation and Artificial Intelligence Tools to Optimize the Performance of the CO2 Sequestration in Coalbed Methane Reservoirs"	An Artificial Neural Network (ANN) was developed to forecast the crucial parameters that affect the performance of the reservoir, e.g., the amount of methane produced concerning CO_2 injected	Mohammadpoor et al. (2012)
13	"Numerical modelling of Gondwana coal seams in India as coalbed methane reservoirs substituted for carbon dioxide sequestration"	Technical feasibility of the $CO_{2.}$ECBM process in Indian coals was carried out using COMET 3	Vishal et al. (2013)
14	"A parametric study of coal mass and caprock behavior and carbon dioxide flow during and after carbon dioxide injection"	The main objective of this paper was to model the effect of injection pressure for CO_2 storage and the possibility of back migration of CO_2 in the atmosphere using COMSOL Multiphysics simulator	Perera et al. (2013)
15	"Current status and technical challenges of CO_2 storage in coal seams and enhanced coalbed methane recovery: an overview"	The global status of CO_2-ECBM technology over the last two decades was overviewed using the CO_2 storage capacity of coalbed, laboratory investigation, modeling, and pilot testing	Li and Fang (2014)
16	"Optimal scheduling for enhanced coalbed methane production through CO_2 injection"	A new deterministic and stochastic model was proposed for CO_2- ECBM production and maximization of total profit	Huang et al. (2014)

Table 1 (continued)

S.N	Title of paper	Significance	References
17	"Investigation of varying composition gas injection for coalbed methane recovery enhancement: A simulation-based study"	It was shown through simulation that if the composition of injected gas altered, there was 6% more methane recovery than the conventional ECBM technique	Sayyafzadeh et al. (2015)
18	"Influence of sorption time in CO_2-ECBM process in Indian coals using coupled numerical simulation"	The role of sorption time for CO_2- ECBM processing Indian coals was investigated using numerical simulation	Vishal et al. (2015)
19	"Optimization of gas mixture injection for enhanced coalbed methane recovery using a parallel genetic algorithm"	Parallel genetic algorithm coupled with ECLIPSE-E300 coalbed simulator for the development of the economic objective function. The proposed methodology gives good revenue with the gas mixture, e.g., N_2/CO_2 ECBM process	Sayyafzadeh and Keshavarz (2016)
20	"Modeling of CO_2 sequestration in coal seams: Role of CO_2-induced coal softening on injectivity, storage efficiency and caprock deformation"	CO_2 sequestration in coal seams was modeled using a coupled-flow deformation model that considers coal softening	Ma et al. (2017)
21	"Simulation of CO_2 enhanced coalbed methane recovery in Jharia coalfields, India"	One numerical model was proposed using COMET3 reservoir simulator for the simulation of CO_2-ECBM recovery	Vishal et al. (2018)
22	"Modeling CH4Displacement by CO2 in Deformed Coalbeds during Enhanced Coalbed Methane Recovery"	The displacement calculation of methane due to CO_2 adsorption in deformed coal was investigated in this chapter. Further, the model was combined with TOUGH2 to simulate the ECBM reservoir	Zeng et al. (2018)
23	"CO_2 storage in coal to enhance coalbed methane recovery: a review of field experiments in China"	A review of past and present ECBM projects has been discussed in this paper and a comparison of this project with globally operated ECBM projects was also presented	Pan et al. (2018)
24	"A review of experimental research on Enhanced Coal Bed Methane (ECBM) recovery via CO_2 sequestration"	A comprehensive review of the experimental methods used in CO_2-ECBM recovery was utilized in this	Mukherjee and Misra (2018)
25	"Thermo-hydro-mechanical-chemical couplings controlling CH_4 production and CO_2 sequestration in enhanced coalbed methane recovery"	THMC model was performed for the CO_2-ECBM recovery	Fan et al. (2019)
26	"Multiscale model for flow and transport in CO_2-enhanced coalbed methane recovery incorporating gas mixture adsorption effects"	A multiscale model was developed for discussing the flow and transport of CO_2 and CH_4 in ECBM recovery incorporating the DFT theory	Le et al. (2020)
27	"Integrated assessment of CO_2-ECBM potential in Jharia Coalfield, India	A numerical simulation study was presented for CO_2-ECBM recovery from Jharia Coalfield India using COMET3 simulation software	Asif et al. (2022b)
28	"Mechanisms in CO_2-enhanced coalbed methane recovery process"	The mechanism involved in the CO_2-ECBM process was discussed in a nutshell	Asif et al. (2022c)
29	"Recent Advances and Perspectives of CO2-Enhanced Coalbed Methane: Experimental, Modeling, and Technological Development"	A review of CO_2-ECBM recovery was presented by following experimental and modeling approaches. Some of the field test results were also elaborated in this review paper	Fan et al. (2023)

Table 2 CO_2-ECBM process: experimental researches

S.N	Title of paper	Significance	Reference
1	"Relationship Of Sorption Capacity to Coal Quality: CO_2 Sequestration Potential of Coalbed Methane Reservoirs in The Black Warrior Basin"	Coal quality and gas sorption capacity of coal quality of The Black Warrior Basin were discussed for CO2 sequestration and ECBM	Carroll and Pashin (2003)
2	"Economics for Enhanced Coalbed Methane (ECBM) and CO2 Sequestration with Horizontal Wells"	The concept of Net Present Value (NPV) was used to discuss the economics of the CO_2-ECBM project	Jikich et al. (2004)
3	"Coalbed methane reservoir data and simulator parameter uncertainty modelling for CO2 storage performance assessment"	This paper uses a qualitative methodology for the estimation of variability and uncertainty in geological storage of CO_2 in coalbeds	Korre et al. (2007)
4	"Gas mixture enhance coalbed methane recovery technology: pilot tests"	Gas mixture Enhanced Coalbed Methane (G ECBM) technology was used for enhanced coalbed recovery. For that two-pilot test project was taken into consideration in China	Fang et al. (2011)
5	"Coal Bed Methane in India: Difficulties and Prospects"	Difficulties for CBM and ECBM extraction were discussed with a case study of the coalfield of the Gondwana basin	Ojha et al. (2011)
6	"Optimizing enhanced coalbed methane recovery for unhindered production and CO2 injectivity"	The effect of gas pressure and stress on the permeability of the CBM reservoir pervaded by CO_2 injection was investigated	Kumar et al. (2012)
7	"Swelling-induced changes in coal microstructure due to supercritical CO_2 injection"	This paper claims that Microcleat closure was obtained by supercritical CO2 flooding in situ by using an X-ray microcomputed tomography flooding apparatus	Zhang et al. (2016)
8	"Effects of Supercritical CO_2 Fluids on Pore Morphology of Coal: Implications for CO_2 Geological Sequestration"	The conceptual model was developed to explain the desorption process for understanding pore morphology under supercritical CO_2 at high-pressure condition	Zhang et al. (2017)
9	"Sorption Kinetics of CH4 and CO2 Diffusion in Coal: Theoretical and Experimental Study"	An experimental and modeling approach was applied to study the diffusion of CO_2 and CH_4 in coal	Naveen et al. (2017)
10	"In-situ disposal of CO2: Liquid and supercritical CO_2 permeability in coal at multiple down-hole stress conditions"	Permeability experiments were analyzed using liquid and supercritical phases of CO_2 in fractured bituminous coal	Vishal (2017)
11	"An experimental investigation of the applicability of CO_2 enhanced coal bed methane recovery to low-rank coal"	CO_2 core flooding tests were conducted on CH4-saturated Victorian brown coal samples to investigate the CO_2 –ECBM potential of the same	Ranathunga et al. (2017)
12	"Adsorption isotherms of CO_2 – CH_4 binary mixture using IAST for optimized ECBM recovery from sub-bituminous coals of Jharia coalfield: an experimental and modeling approach"	Competitive adsorption of CO_2-CH_4 was studied using the IAST model. MATLAB code was developed for the iterative calculation from IAST	Asif et al. (2019a)
13	"Dynamic Fluid Interactions during CO_2-Enhanced Coalbed Methane and CO_2 Sequestration in Coal Seams. Part 1: CO_2–CH_4 Interactions"	NMR technique was applied for the CH_4 desorption, and CO_2 ECBM flooding was studied under in-situ condition	Zheng et al. (2020)
14	"Liquid CO_2 injection to enhance coalbed methane recovery: An experiment and in-situ application test"	This study investigated the ECBM recovery by liquid CO_2 injection under laboratory condition	Wei et al. (2021)
15	"The effect of subcritical and supercritical CO_2 on the pore structure of bituminous coals"	The effect on porosity, total pore volume, pore size distribution, and fractal were investigated after treating coal samples with sub and super-critical CO_2	Cheng et al. (2021)
16	"Laboratory experiments of CO_2 enhanced coalbed methane recovery considering CO_2 sequestration in a coal seam"	The synergistic effect of the CO_2-ECBM process was studied using a large-scale multifunctional apparatus	Zhang et al. (2023)
17	"Influence of competitive adsorption, diffusion, and dispersion of CH_4 and CO_2 gases during the CO_2-ECBM process"	Competitive adsorption, diffusion, and dispersion were redefined to discuss the methane displacement in the CO_2-ECBM process	Asif et al. (2024)

Table 3 Pilot test and commercial project for CO_2-ECBM processes

S.N	Pilot tests	Location	Methodology	Objectives and results	Reference
1	Allison Unit CO_2-ECBM Pilot 1995–2001	San Juan Basin, New Mexico, USA	5 Spot pattern, 1 injector, and 4 producers well	A significant increment of 17% was observed in CH_4 production after the CO_2 injection into the reservoir (77%–95%)	Reeves and Taillefert (2003), Shi and Durucan (2005)
2	Fenn-Big Valley CO_2-ECBM Pilot, 1998–2000	FennBig Valley in Central Alberta Canada	A micro pilot test was conducted with 1 injection and 1 production well	Pure CO_2 and flue gas were injected Methane production was increased by 147%	Gunter et al. (2005)
3	Cv¯ictus CO_2 injection pilot (Deep Mannville coal) 04.2021–02.2022	Mikwan area, near Red Deer, Alberta	ECBM Pilot test with single production and an observation well	CO_2 injection viability and quantify the migration of water to evaluate the significant mechanism for improving the Enhanced Hydrogen Recovery process	Yang et al. (2023)
4	RECOPOL project 2003–2005	Upper Silesian Basin in Poland	ECBM Pilot project with 1 production and 1 injection well;	The main goal of this project was to demonstrate whether CO_2 injection under European Conditions is feasible	Pagnier et al. (2005)
5	CO_2-ECBM process 2004–2007	Ishikari coal field in Hokkaido, Japan	Single production and injection well	Production increased to 200% during the initial days of CO_2 injection and gradually decreased	Fujioka et al. (2010)
6	CO_2-ECBM pilot, 2003–2004	Qinshui Basin, Jincheng City, Southeast of Shanxi Province, China	Single production and injection well	Approximately 200 t of CO_2 was injected; Stopped due to operation problems	Liu et al. (2020)

molecular bonds between gas and coal molecules. Inside the coal structure, the coal molecules are intact, with equilibrium forces between them. However, a force imbalance occurs between the surface and inside molecules. Therefore, potential adsorption sites are created at the surface, which attract the gas molecules for adsorption (Asif et al. 2019a; Mohammad et al. 2012; Ottiger et al. 2008; Shimada et al. 2005; Yu et al. 2014). On the surface of the coal, the gas molecules adhere to the surface by weak van der Walls forces. The van der Walls equation has been given in Eq. (1):

$$\left(P + \frac{a}{V^2}\right) \times (V - b) = RT \tag{1}$$

When CO_2 is injected in coal seams, it decreases the partial pressure of CH_4 without decreasing the overall reservoir pressure, which leads to fast desorption of CH_4 and adsorption of CO_2 in its place (Norouzbahari et al. 2015; Perera et al. 2012; J. Q. Shi and Durucan 2005). However, the desorption of CH_4 is incomplete. A competitive adsorption phenomenon between CO_2 and CH4 is a function of concentration (Asif et al. 2018a, b). It may be noted from Eq. (1) that the measure of intermolecular forces represented by the ‘a’ value of CO_2 is more than CH_4 (Table 4), which suggests that CO_2 would be preferentially adsorbed over CH_4.

Due to the distinct properties of $CO_{2,}$ as shown in Table 4, the preferential adsorption leads to adsorption capacity differences between 2 to 10 times (Asif et al. 2022a). Therefore, storage of CO_2 in coalfield affords long-term stability with reduced risk of back migration of CO_2 into the atmosphere.

Furthermore, it is identified that the preferred depth for CO_2 sequestration in coal seams is over 800 m since, at this depth, CO_2 is a supercritical phase with liquid-like density (Pashin and Mcintyre 2003), thus high storage capacity, and efficient use of coal porosity. It may be observed from Fig. 3b that CO_2 is injected at point 1, where both pressure and temperature are at surface conditions. Supercritical CO_2 also possesses higher adsorption capacity than subcritical CO_2 and has more potential to displace methane (Fan et al. 2020). The competitive adsorption for adsorption sites between CO_2 and CH_4 is depicted in Fig. 3c, with a co-adsorption adsorption isotherm shown in Fig. 3d.

Table 4 Major properties of CO_2 and CH_4 for comprehending competitive adsorption (Vishal and Singh 2016)

S.N	Properties	CO_2	CH_4
1	Kinetic diameter (nm)	0.33	0.38
2	van der Walls constant (a) (bar L^2/mol^2)	3.658	2.30
3	Critical pressure (MPa)	7.38	4.641
4	Critical temperature (°C)	31.8	82.01

4 Geological review of carboniferous coal deposits of Kazakhstan

Kazakhstan, the ninth largest country in the world by land mass, possesses substantial coal reserves in the central and northeastern parts of the country, estimated to be 170 Bt, with coal production of 103 Mt/year from 400 operating mines (Ammosov et al. 1973a, b, Azizov et al. 2013). Two-thirds of Kazakhstan's coal is bituminous and subbituminous coal. Four carboniferous coal formations are described here, notably the Karagandy, Teniz-Korzhinkol, Ekibustuz, and Chu coal basins (Fig. 4). Except for the Chu basin, the three remaining are major coal-producing coalfields of Kazakhstan.

(1) Karagandy coal basin is the country’s main coal-producing basin (around 37 Mt/year) in the Karagandy region. The basin enriches all types of coal (from lignite to anthracite) in the main seven coal formations (Shahan, Tentek, Dolyn, Nadkaragnda, Karaganda, Ashlyar, and Akkuduk) of Lower-Middle-Upper Carboniferous age with a thickness between 350–850 m.
(2) Teniz-Korzhynkol coal basin is located in the Akmola region, which is 200 km southwest of Astana and includes four Lower Carboniferous coal-producing deposits (Qosmurun in the west, Qyzylsor in the south, Bozshasor in the north and Saryadyr in the southeast). This coal basin includes all coal types from lignite to anthracite in the Karagandy, Ashlyar, and Akkuduk coal formations of thickness between 430 to 450 m). This coal basin produces 3 Mt/year.
(3) Ekibastuz coal basin is located in the Pavlodar region and contains Lower Carboniferous coal formations. Coal is being produced by three giant open-pit mines (Bogatyr, Severniy, and Vostochniy) in the basin. The basin includes all coal types, from lignite to anthracite, in Nadkaragandy, Karagandy, Ashlyar, and Akkuduk coal formations. The coal production from the basin is about 30 Mt/year.
(4) The Chu coal basin is in the Zhambyl region. It has all coal types (from lignite to anthracite) in the Lower Carboniferous coal formations (Visean and Tunisian) ranging between 350 and 850 m thick.

The stratigraphic column of the four coal basins is shown in Fig. 5.

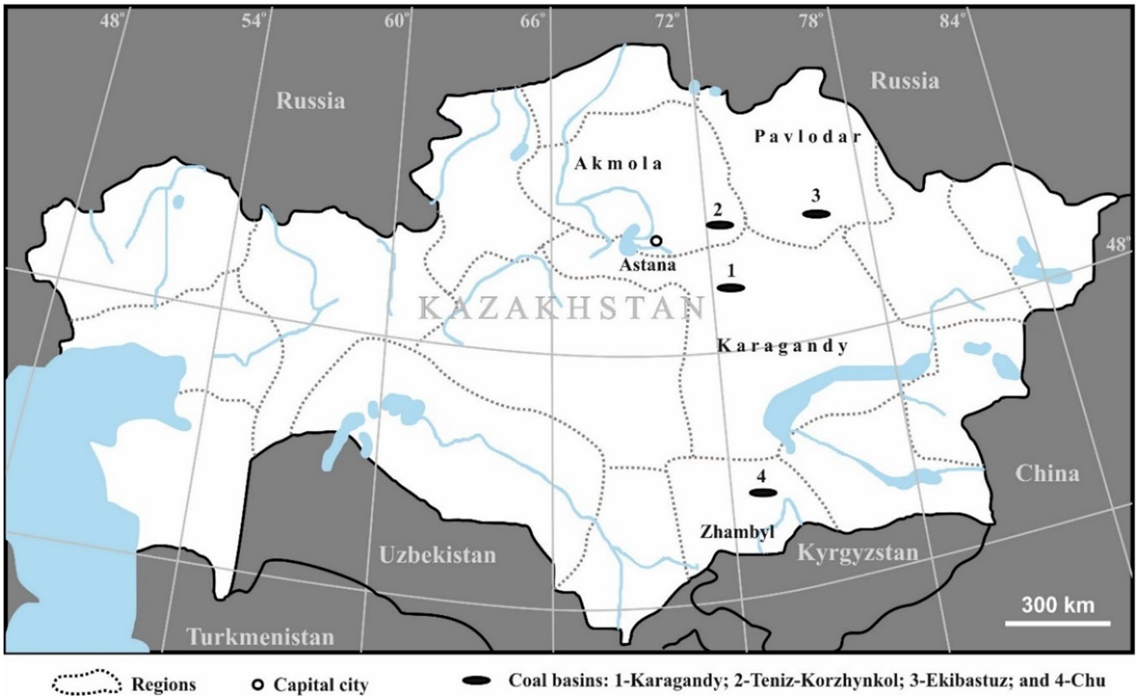


Fig. 4 The Carboniferous coal basins of Kazakhstan

4.1 Karagandy coal basin coal basin

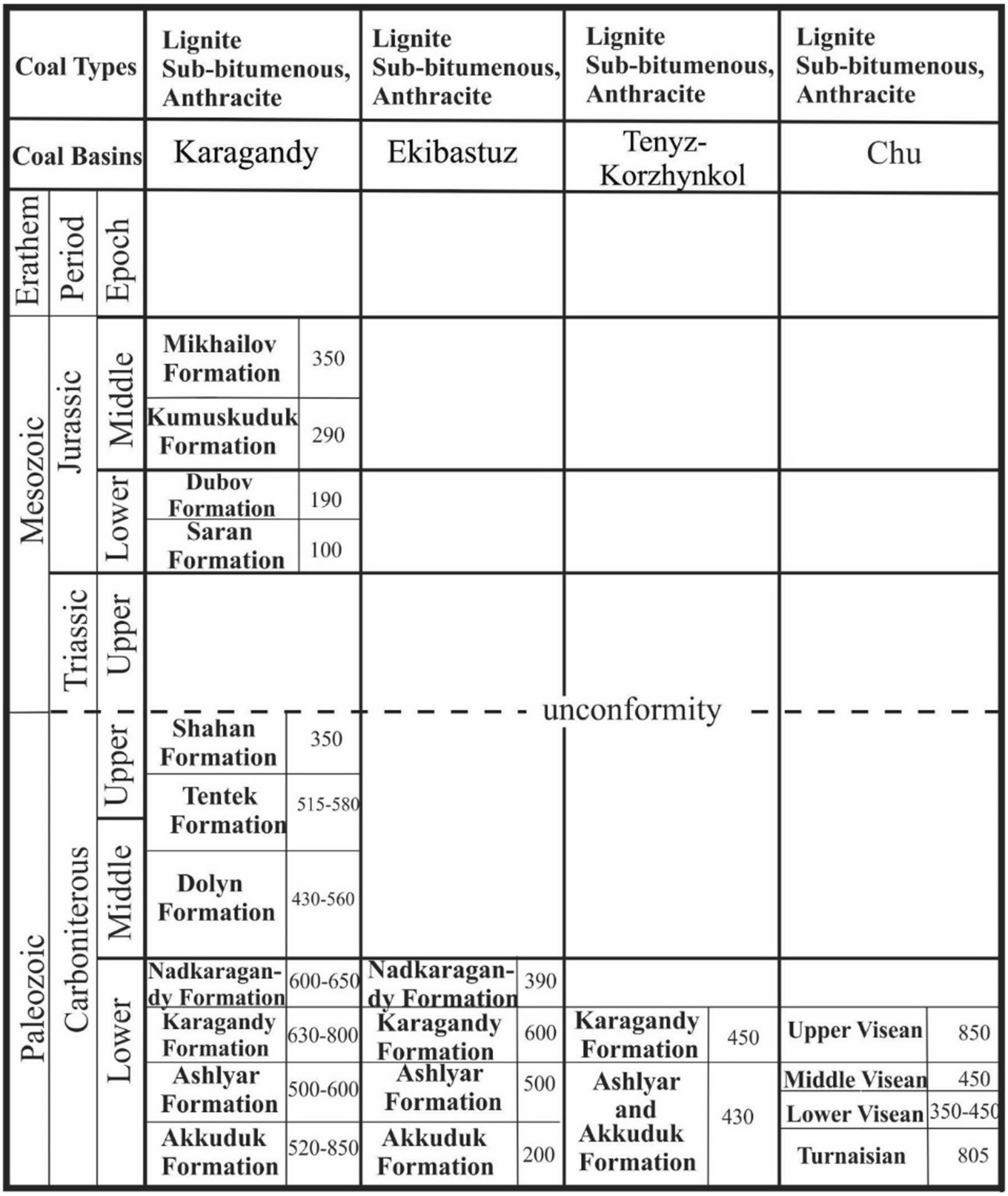
The Karagandy coal basin, a deep synclinal sub-latitudinal structure covering approximately 3600 km^2, has the largest area in Kazakhstan with a width of approximately 30 km east to west and a length of 120 km measured north to south. It hosts the three synclinal trough separated by the Alabas and Maikuduk uplifts of Tentek, Churubay-Nurun, and Dubov (Fig. 6). The basin contains mainly Devonian strata of volcanic-sedimentary and sedimentary rocks of sandstone (36%), siltstone (30%), mudstone (27%) and others (10%) of tuffs, carbonate rocks and conglomerate. While the Carboniferous sequence in the basin contains sandstone and clay, it ranges up to 4500 m and includes 80 coal seams. The depth of the Carboniferous coal formation is down to 1800 m, while the Jurassic coal formation is found in depths from 300 to 450 m. The Lower-Middle Carboniferous coal formations consist of deep coal seams in the Karagandy, Ashlyar, and Akkuduk formations, while other coal seam formations are shallow. These three coal basins host all coal varieties, from lignite to anthracite. The seams of interest here lie in the carboniferous formation. The deeper coal seams were highlighted in the red dotted line as a potential target for CO$_2$ storage.

The coal has many fractures ranging between 2 mm × 2 mm and 6 mm × 6 mm. The coal has a low sulfur content of up to 1.5% and a moisture content of up to 14%. The basin contains one of the largest concentrations of methane gas, ranging between 22–25 m^3/t. The ash content of coals varies from 20%–30%, while vitrinite reflectance (*R*o) ranges from 1.80%–2.03%. The total coal reserves of the basin are 43.1 billion tons (Azizov et al. 2013). Nine mineable underground coal mines are shown in Fig. 6.

4.2 Teniz-Korzhinkol coal basin

The Teniz-Korzhynkol basin occurs as a large brachy synclinal structure in the northern part of the Shydertyn megasyncline. It includes the four small syncline structures of Qosmurun, Qyzylsor, Bozshasor, and Saryadyr, formed as coal deposits and mined only by open-pit from the Saradyr coal deposit (Fig. 7).

The Basin area is approximately 400 km^2, with a width of 20 km east to west and a length of 20 km north to south. The coal basin hosts about 60–70 coal seams. The thickness of coal seams fluctuates from 1.5 m to 50 m, buried at a depth of up to 1800 m. Coal seams are found in the Lower Carboniferous formations of Karagandy, Ashlyar, and Akkuduk and occur within sedimentary rocks of grey to dark clay, marl, mudstone, sandstone, and siltstone. Cambrian and Devonian basements primarily originate in the northwest part of the basin. The primary sediments of the basements are limestone, shale, and marl, with a thickness of 200 m. Magmatic intrusions



Coal Types			Lignite Sub-bitumenous, Anthracite		Lignite Sub-bitumenous, Anthracite		Lignite Sub-bitumenous, Anthracite		Lignite Sub-bitumenous, Anthracite	
Coal Basins			Karagandy		Ekibastuz		Tenyz-Korzhynkol		Chu	
Erathem	Period	Epoch								
Mesozoic	Jurassic	Middle	Mikhailov Formation	350						
			Kumuskuduk Formation	290						
		Lower	Dubov Formation	190						
			Saran Formation	100						
	Triassic	Upper								
			unconformity							
Paleozoic	Carboniterous	Upper	Shahan Formation	350						
			Tentek Formation	515-580						
		Middle	Dolyn Formation	430-560						
		Lower	Nadkaragandy Formation	600-650	Nadkaragandy Formation	390				
			Karagandy Formation	630-800	Karagandy Formation	600	Karagandy Formation	450	Upper Visean	850
			Ashlyar Formation	500-600	Ashlyar Formation	500	Ashlyar and Akkuduk Formation	430	Middle Visean Lower Visean	450 350-450
			Akkuduk Formation	520-850	Akkuduk Formation	200			Turnaisian	805

Fig. 5 A schematic stratigraphic column showing coal types and formations (with thickness in meters) of the selected four coal basins of Kazakhstan (modified after Ammosov et al. 1973a, b, Azizov et al. 2013)

are mainly composed of granite-porphyry, found dikes, sills, and a deeply buried batholith in contact with highly metamorphosed coals. The coal seams usually have bituminous coal to anthracite (probably graphite), give high ash yields of 20%–45%, contain between 0.2%–1.8% sulfur, and have up to 10% moisture content. Total coal reserves in the basin are estimated to be about 2.6 billion tons (Ammosov et al. 1973a). Hence, this coal basin is a potential target for CO_2 storage in deeper coal seams.

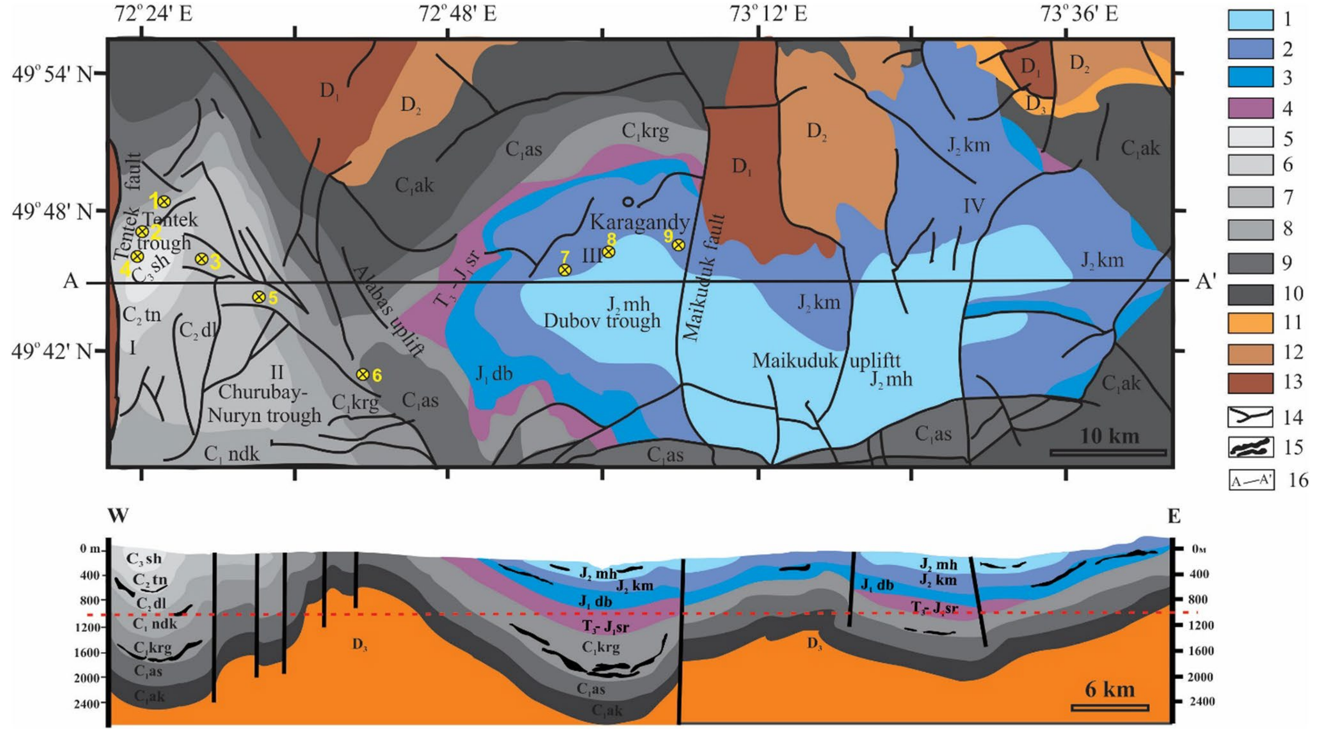


Fig.6 Geological cross-section of the Karagandy coal basin showing Lower Jurassic coal-bearing strata : 1. Middle Jurassic Mihailov Formation (J_2mh, mudstone); 2. Lower Jurassic Kumuskuduk Formation (J_1km, siltstone); 3. Lower Jurassic Dubov Formation (J_1db, Sandstone); 4. Upper Triassic-Lower Jurassic Saran Formation (T_3–J_1sr, gravels, conglomerate); Carboniferous formations from 5.Upper Carboniferous Shahan Formation (C_3sh), 6. Middle Carboniferous Tentek Formation (C_2te), 7. Middle Carboniferous Dolyn Formation (C_2do), 8. Lower Carboniferous Nadkaragndy Formation (C_1na), 9. Lower Carboniferous Karagandy Formation (C_1ka) to 10. Lower Carboniferous Ashlyar Formation (C_1ash); 11. Upper Devonian; 12. Middle Devonian; 13. Lower Devonian; 14. Faults; 15. Coal seams; 16. A cross-sectional profile (modified after Azizov et al. 2013); Mining area: I-Tentek; II- Churubay-Nuryn; III-Karagandy; IV-Verhnesokur; Underground mines: 1-Tentek; 2-Kazakhstan; 3-Shahtins; 4-Lenin; 5-Abay; 6-Saran; 7-Kuzembayev; and 8-Kostenko) (Sabitova 2015; Junussov et al. 2024)

4.3 Ekisbastuz coal basin

The Ekibastuz coal basin is restricted to the asymmetrical graben-syncline covering over 155 km^2 with a width of 8.5 km and a length of 24 km, extending in the northwestern direction. It is bounded in the northeast and southeast by significant faults with amplitudes of 1000 m and 150 m, respectively, as shown in Fig. 8. The coal basin is stratified with a Devonian basement and volcanic shale deposits of mudstone and sandstone. The Lower Carboniferous sequence shows coal-bearing formations of Nadkaraganda, Karaganda, Ashlyar, and Akkuduk, deposited with dark grey mudstone, siltstone, and green, fine-grained sandstones and containing around 6 mineable coal seams and 15 unmineable coal seams. The coal seams range from 8–30 m in thickness, buried at a 530–680 m depth. The coal seams in the basin are mainly characterized from lignite to anthracite. Ash content of the coal seams ranges from 30% to 41%, while sulfur and moisture content range between 0.4% to 1% and up to 14.2%, respectively. The coal seams contain methane and nitrogen gases from 4–10 m^3/t, with total coal reserves of the basin at around 9.7 billion tons (Ammosov et al. 1973a).

4.4 Chu coal basin

The Chu coal-bearing basin occurs as a brachy synclinal structure in the Chu-Sarysu Basin, which is the second-largest sedimentary basin in Kazakhstan (Fig. 9). The southwest and northeast boundaries of the sedimentary basin are marked by the parallel Karatau and Zhalair-Naiman faults, respectively (Box et al. 2012). The coal-bearing formations as a coal basin originated between the tectonic faults. Mesozoic sediments mainly cover the coal basin as a sand desert (a width of 15–30 km), forming the Moyinkum deflection.

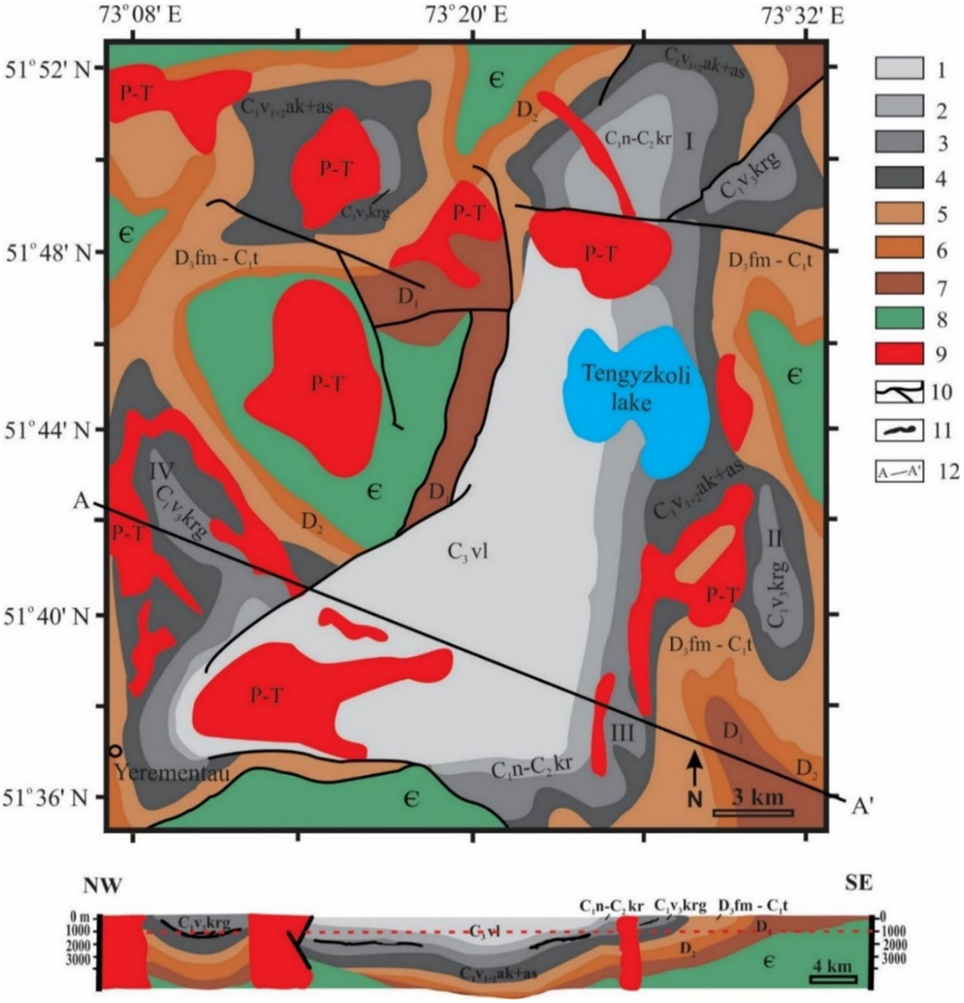


Fig. 7 Geological cross-section of the Teniz-Korzhinkol coal basin showing Carboniferous and Devonian sequences: 1. Upper Carboniferous (Vladimirov Formation); 2. Middle Carboniferous (Kirey Formation); 3. Middle-Lower Carboniferous (Karagandy coal Formation); 4. Lower Carboniferous Middle-Lower Visean (Ashlyar and Akkuduk coal Formations); 5. Upper Devonian (Famennian)-Lower Carboniferous (Tournaisian); 6. Middle Devonian; 7. Lower Devonian; 8. Cambrian; 9. Permian–Triassic magmatic intrusions; 10. Faults. 11. Coal seams; 12. A cross-sectional profile (modified after Ammosov et al. 1973a; Azizov et al. 2013). Coal deposits: I-Bozhshasor; II- Saryadyr (currently coal mined); III- Qyzylsor and IV- Qosmurun

Significant four coal deposits of Kamkaly, Karakol, Alexandrovskoe, and Kasymtobe are included in the basin. Coal deposits in the basin were traced along the strike for 100 km. More productive coal formations in the Lower Carboniferous host about 13 coal seams. All coal seams in lens shapes reach a thickness from 0.3–2.5 m to 4.5 m to 15 m and are considered mineable. The basin has deep coal seams at a depth of 2500 m. The coal seams are mainly bituminous coal to anthracite coal types in the Lower Carboniferous Tournaisian and Visean formations (Fig. 9). Furthermore, these are interbedded with carbonate and terrigenous sediments of grey limestone breccias and marl, conglomerate, greenish-grey fine-grained sandstone, and siltstones. The coal seams usually yield a high ash content between 40%–46%, have up to 2.3% sulfur content, and contain moisture content up to 11.4%. Total coal reserves are 3.3 billion tons (Ammosov et al. 1973a; Azizov et al. 2013). Therefore, this coal basin is a potential target for CO_2 storage in deep unmineable coal seams.

4.5 Paleogeographic evolution of the carboniferous coal basins for CO_2 storage

The paleogeographic evaluation of the four coal basins suggests that coal formation belongs to the Carboniferous age as per the literature of Ammosov et al., (1973a, b) and Azizov et al. (2013). According to the review of the paleogeographic evolution during the Carboniferous time in Kazakhstan, the most economical coal was deposited mainly in the Lower and Middle Carboniferous periods. The paleogeographic outline of the Lower and Middle Carboniferous, which inherited the characteristics of the deep marine basins in the western, southern, and eastern areas, developed in the northern region, extending between the northern and the central-southern upland. Extensive low-relief carbonate shelves were typical for central areas. On the Kazakhstan continent, behind the volcanic belt, large marsh-lacustrine systems accumulated thick coal beds of Karagandy, Ekibastuz, Tenyz-Korzhynkol, and Chu (Daukeev et al. 2002), as shown in Fig. 10. The Carboniferous period was the time for the climatic transition. The Lower Carboniferous generally

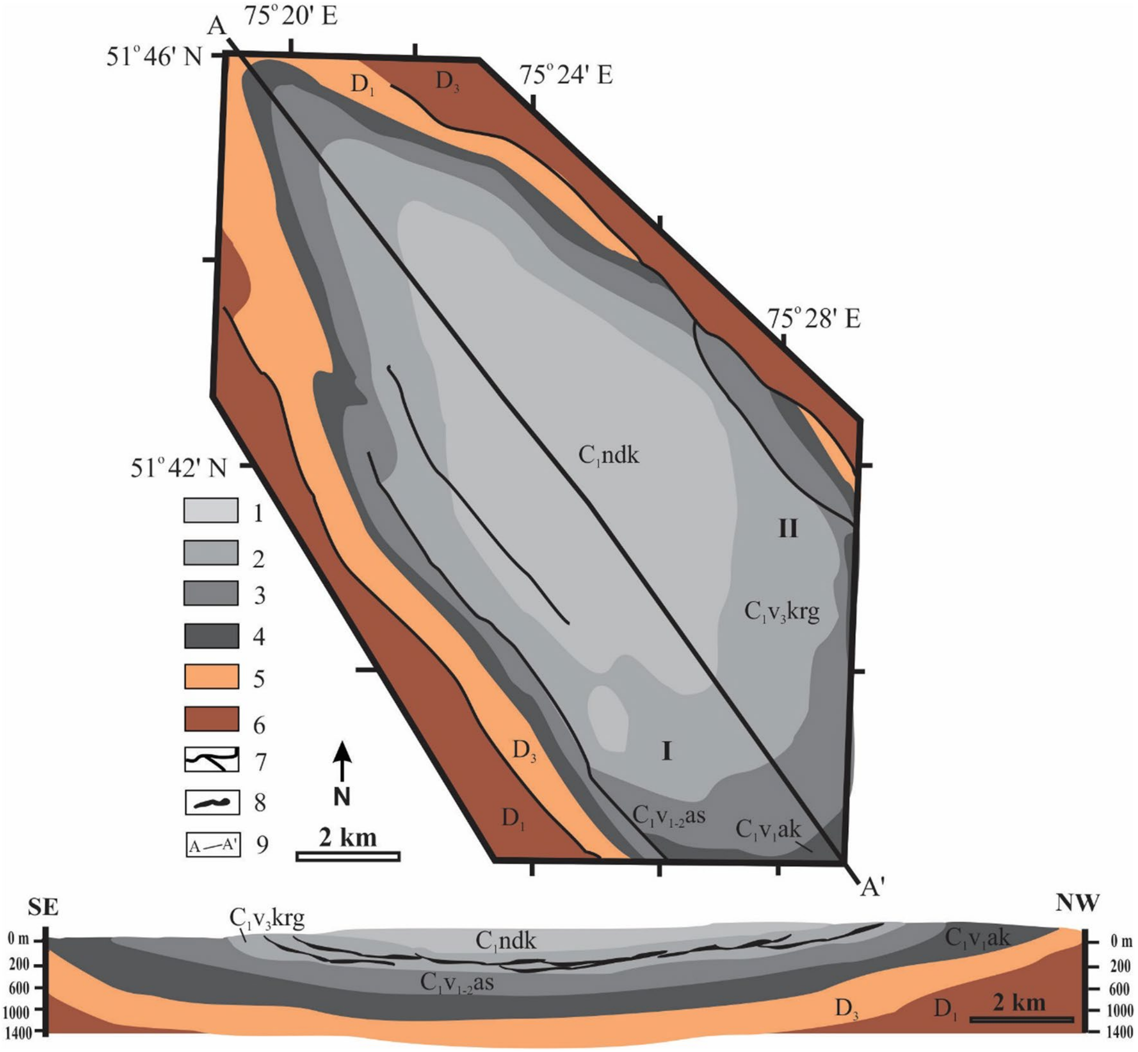


Fig. 8 Geological cross-section of the Ekibastuz coal basin showing the Lower Carboniferous coal-bearing formations of 1. Nadkaragndy (C_1 ndk), 2. Karagandy (C_1 krg), and 3. Ashlyar ($C_1v_{1\text{-}2}$ as, Middle-Lower Visean); 4. Akkuduk; Devonian basements of 5. Middle Devonian, 1. Lower Devonian; 7. Faults; 8. Coal seams; 9. A cross-sectional profile (Modified after Azizov et al. 2013).

had a more humid climate, which was more favorable for coal occurrence.

In contrast, the Upper Carboniferous had a warming trend and generally became drier, unfavorable for coal deposits (Rowley et al. 1985). In the late Lower Carboniferous, the oceanic crust resumed subduction on all the margins of Kazakhstan. This resulted in forming the Valer'yanovka island arc and the Balkhash–Ile volcanic-plutonic belt, intense volcanic-arc activity, and the closure of some inter-arc basins. Vast lake bog plains with abundant coal accumulation existed at the back of the volcanic belt in Kazakhstan, occurring thick coal measures. A single marine shelf basin with terrigenous–carbonate sedimentation existed in most of Kazakhstan (Korobkin and Buslov 2011).

5 The CO_2 storage capacity for the coal basins

The required data has been collected from previous literature (Ammosov et al. 1973a, 1973b; Azizov et al. 2013). Information on four carboniferous coal deposits was shown in Table 5.

It may be noted from Table 5, that due to the unavailability of data on Kazakhstan coalfields and for the sake of brevity, only average values have been considered. The CO_2 storage capacity of the coal seam (*S*, *Mt*) was generally found using the formula proposed by the U.S. Department of Energy (Goodman et al. 2011):

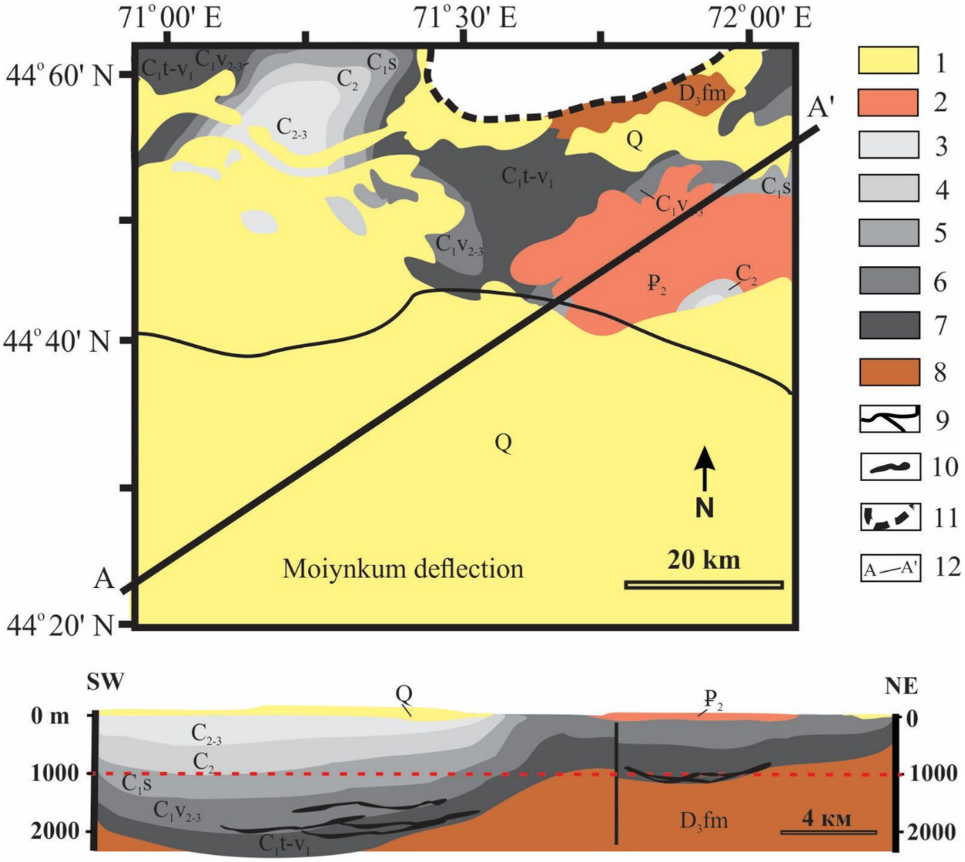


Fig. 9 Geological cross-section of the Chu coal basin showing 1. Quaternary; 2. Eocene; 3. Middle-Upper Carboniferous; 4. Middle Carboniferous; 5. Lower Carboniferous; 6. Lower Carboniferous Middle-Upper Visean; 7. Lower Carboniferous Lower Visean and Turnaisian; 8. Upper Devonian; 9. Faults; 10. Coal seams; 11. Basin counter line; 12. A cross-sectional profile (Junussov and Mustapayeva 2024)

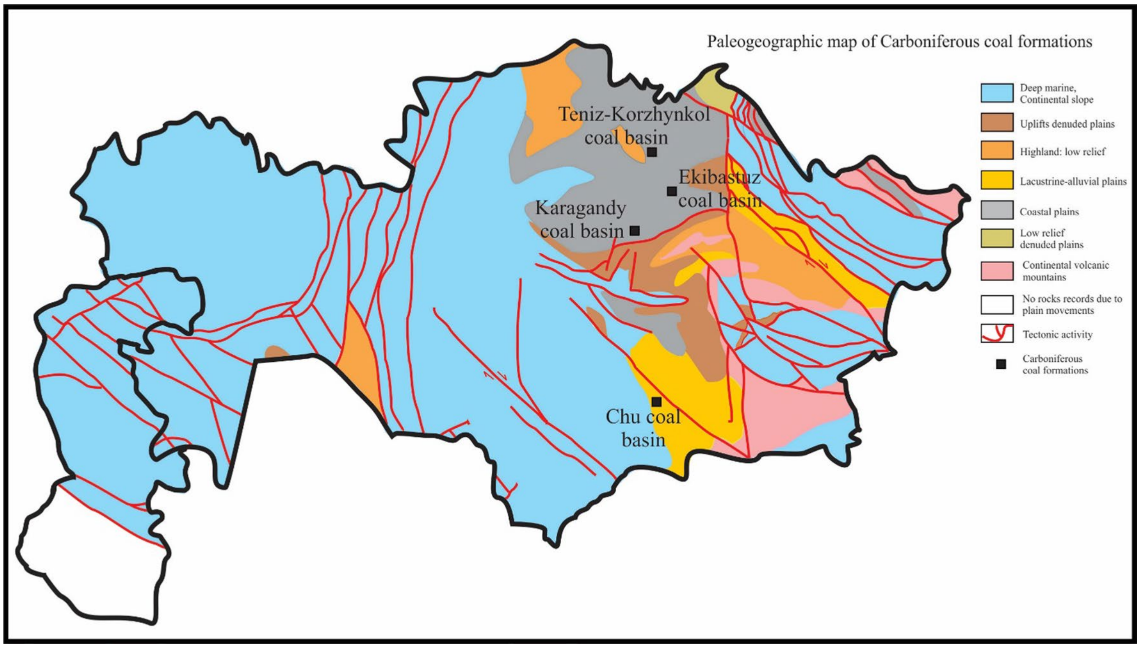


Fig. 10 Paleogeographic evaluation of Kazakhstan showing the Lower Carboniferous (modified after (Korobkin and Buslov 2011))

Table 5 Collected data for the three coal deposits of Kazakhstan (Ammosov et al. 1973a; Ammosov et al. 1973b; Azizov et al. 2013)

S.N	Coal basins	$D_{\max}$ (m)	A_T (km^2)	T_c (m)	N	T_r (Bt)	A	M	C
1	Karagandy	1800	3600	80–100	65–80	43.1	20–30	3–7	84–93
2	Teniz-Korzhinkol	1800	400	1.5–50	60–70	2.6	40–45	3–12	78–91
3	Ekibustuz	680	155	8–30	6–15	9.7	30–41	8–14.2	84–89
4	Chu	2150	240	0.3–15	13	3.3	40–46	0.7–1.6	84–92

$D_{\max}$ maximum depth of coal seam, A_T Total area of reservoir, T_c Thickness of the coal seam, N Number of coal seams, T_r Total reserve, A Ash content, M Moisture content, C carbon content

$$S = A_c \times T_c \times \rho_c \times E_f \times V_{CO_2} \times \rho_g \tag{2}$$

where A_c is the area of the coal seam (km^2), T_c is the thickness of the coal seam (m), ρ_c is the density of coal (g/cc), E_f is the storage efficiency of coal which was assumed as 57% (George Hall 2007), V_{CO_2} is the adsorption capacity of coal seams concerning CO_2 (Langmuir constant, m^3/t), ρ_g is the density of CO_2 at different depth (cc/g).

The area of the coal seam (A_c) may be found using the below-mentioned formula or Eq. (3):

$$\text{Area of coal seam} = \frac{\text{Total reserve}}{\text{Density of coal} \times \text{Thickness of coal seam} \times \text{Number of coal seams}}$$

$$A_c = \frac{T_r}{\rho_c \times T_c \times N} \tag{3}$$

In this equation, the coal seam is assumed to be a tabular shape. Therefore, a new formula was proposed and used in this paper for calculating the CO_2 storage capacity (S_t) of a particular coal seam, as shown in Eq. (4). The methodology adapted by US DOE for the volumetric calculation of CO_2 storage in unmineable coal seams was slightly modified. Instead of area, thickness, and density of the coal seam, coal reserve and number of coal seams was used. Simple geometry was applied and a formula for CO_2 storage in tabular coal seams was developed. This value was doubled since CO_2 has around 2 times more adsorption capacity than CH_4 in coal (Mohammad et al. 2012; Zhang et al. 2014). The formula given by the U.S. Department of Energy was slightly modified as:

$$S_t = \frac{T_r \times E_f \times V_{CO_2} \times \rho_g}{N} \tag{4}$$

The Langmuir volume constant was also used in this formula which was a modified version of the Langmuir volume correlation given by Mohanty et al. (Mohanty et al. 2018). In this research paper, authors have developed a statistical correlation between the chemical composition of 39 coal samples with their respective Langmuir volume constants of methane. This value was doubled since CO_2 has around 2 times more adsorption capacity than CH_4 in coal (Mohammad et al. 2012; Zhang et al. 2014). The formula for calculating the Langmuir volume constant for CO_2 has been shown in Eq. (5):

$$V_{CO_2} = 2 \times \left[1.63\left(\frac{C}{A+M}\right)^2 + 14.5\left(\frac{C}{A+M}\right) - 11.27\right] \tag{5}$$

It is worth mentioning that adsorption capacity is a function of temperature and pressure which was already considered for the experimentation of adsorption capacity of methane (Mohanty et al. 2018). The Langmuir constant of CH_4 was utilized in this paper for finding the storage capacity of coal concerning CO_2.

The real gas equation has been used to calculate the variable density (Fan et al. 2023):

$$\rho_g = \frac{PM}{ZRT} \tag{6}$$

where P is pressure, M is molecular mass, Z is compressibility, R is gas constant and T is temperature.

In Eq. (6), the following relations, and values have been taken (Lu et al. 2021):

$$P = 0.0049 \times D + 14.684 \tag{7}$$

$$T = 0.0285 \times D + 9.4282 \tag{8}$$

where D is depth in meters, P is in MPa and T is in ℃

The values of M, Z, and R have been taken as 44.01, 0.449, and 8.314 J/mol.K respectively. Using Eq. (6), (7), and (8), the density of CO_2 was derived as (Lu et al. 2021):

$$\rho_g = -7 \times 10^{-6} D^2 + 0.1248D + 537.09 \tag{9}$$

It may be noted that this formula has been derived for supercritical CO_2 of compressibility 0.499 (Lu et al. 2021). However, this formula may be used for the Ekibustuz coal field in which the known depth of unmineable coal seams does not reveal the supercritical condition of CO_2. In contrast, the depth at which supercritical conditions are met is highly variable and mainly contingent on depth, surface temperature, hydrostatics, and the geothermal gradient of the reservoir (Perera et al. 2011; Zhao et al. 2022). The basin temperature (T) and hydrostatic pressure (P_{hyd}) were defined in Eq. (10) and Eq. (11) respectively:

$$T = T_{\mathrm{s}} + G \times D \tag{10}$$

$$P_{\mathrm{hyd}} = \rho_{\mathrm{w}} \times g \times D \tag{11}$$

From Eq. (10) and Eq. (11), the basin pressure may be defined as:

$$P = \frac{\rho_{\mathrm{w}} \times g}{G}\left(T - T_{\mathrm{s}}\right) \tag{12}$$

where T_s, G, and g are the surface temperature, geothermal gradient, the density of water, and gravitational constant (9.8 m/s^2) respectively. The basin pressure was similar to hydrostatic pressure in sedimentary basins such as coal and the geothermal gradient varies from 20 ℃/km to 60 ℃/km (Kolawole and Evenick 2023). However, due to the insufficiency of data on the Kazakhstani carboniferous coal basins, the average and common geothermal gradient of 27 ℃/km was presumed (Abuov et al. 2020). It must be noted that different compressibility has been already used for the calculation of the Langmuir volume based on pressure and temperature that was used in the proposed formula for computing the CO_2 storage capacity of coal seams.

The adsorption capacity of coal concerning CO_2 may be experimentally calculated using several methods e.g., Langmuir equation, Toth equation, UNILAN equation, Dubinin–Astakhov (D–A) and Dubinin–Radushkovich (D–R) equations, 2D equations of state, D–R equation and other methods (De Silva et al. 2012). However, one formula table as Table 6 was given for calculating the CO_2 storage capacity of coal seams.

The CO_2 storage capacity for the coal seams was found for these coalfields using the proposed formula in this paper. The ideal depth of coal seams for CO_2 storage is roughly 800 m for reasons stated earlier. Table 7 shows the CO_2 storage capacity for the carboniferous coal basins with ρ_g and V_{CO_2} for the respective coalfields.

Table 7 Calculated values for the CO_2 storage capacity for the unmineable coal seams of carboniferous coalfields of Kazakhstan

S.N	Coal basins	ρ_g (g/cc)	V_{CO_2} (m^3/t)	S_t (Bt)
1	Karagandy	0.74	98.90	24.60
2	Teniz-Korzhinkol	0.74	36.42	0.61
3	Ekibustuz	0.62	45.09	14.02
4	Chu	0.77	48.44	5.42

The Karagandy coal basins show the highest CO_2 storage capacity among Kazakhstan's three major coal basins that satisfy the 800 m depth criterion. Karagandy coal basin shows excellent adsorption capacity for CO_2 (V_{CO_2}) towards coal. The geology of the coal basin also plays an essential role as the Karagandy coalfield has low ash and moisture content among the three coalfields. Furthermore, Karagandy coalfields have a huge methane content of about 22–25 m^3/t (Azizov et al. 2013). The unmineable coal seams of the Karagandy coal basins may be employed for ECBM recovery to offset the sequestration cost. The supercritical CO_2 has a higher storage capacity as the density of CO_2 increases in the supercritical phase (Zhao et al. 2022). However, Ekibustuz shows a relatively higher storage capacity except Karagandy coal basin. The reason for this may be understood with the help of the proposed formula and data of the Ekibustuz coal basin. Ekibustuz has a huge coal reserve (T_r) and less no of seams (N) as shown in Table 5. Therefore, despite the known depth not being related with CO_2 as supercritical fluid, a relatively high CO_2 storage capacity of 14.02 billion Bt has been calculated for the Ekibastuz coal basins using this formula.

The Teniz-Korzhinkol coal basin shows the lowest value for CO_2 storage, as this coal has high ash and moisture content. Thus, the adsorption capacity of CO_2 towards coal was reduced, and further storage amount in coalfield was substantially diminished. Furthermore, the low coal reserve was also the reason for the lowest storage capacity for CO_2.

Table 6 Different formulas for calculating CO_2 storage in coal seams (Han et al. 2022; Liu et al. 2023)

S.N	CO_2 storage capacity (S_t)	Equation*
1	TCGSC assessment	$S_{\mathrm{th}} = A_{\mathrm{c}} \times T_{\mathrm{c}} \times \rho_{\mathrm{c}} \times V_{CO_2} \times \rho_{CO_2}$
2	ECGSC assessment	$S_{\mathrm{eff}} = S_{\mathrm{th}} \times RF$
3	Unexploited coal seams	$S_{\mathrm{t}} = \rho_{CO_2} \times T_{\mathrm{r}} \times \left(n_{\mathrm{ab}} + n_{\mathrm{s}} + n_{\mathrm{f}}\right) \times 10^{-3}$
4	Residual coal in producing and abandoned mines	$S_{\mathrm{t}} = \rho_{CO_2} \times G \times RF \times ER \times 10^{-4}$ $G = R_{\mathrm{r}} \times C_{\mathrm{g}}$
5	Mined out areas	$S_{\mathrm{t}} = V_{(CO_2)_F} \times \rho_{CO_2} \times 10^{-3}$

*The meaning of each term is given in the nomenclature table

6 Conclusions

CO_2-ECBM recovery aligns with two major sustainable development goals (SDG) of the United Nations i.e., goals 7 and 13. Goal No. 7 states that by 2030 it is recommended to provide affordable, clean, and modern energy to every household. Furthermore, goal No. 13 sheds light on the urgent action to be taken to combat climate change and its impact. CO_2 sequestration in unmineable coal seams is vital to climate action, and coalbed methane provides lower carbon content energy needs. Based on the current study, the following conclusions may be drawn:

(1) The detailed geological review of the coal basins reveals that all significant coal types are present in the studied basins: lignite, sub-bituminous, and anthracite coal.
(2) The unmineable coal seams lying below 800 m of three carboniferous coal may be employed for CO_2 storage to reduce the emission of anthropogenic CO_2 from Kazakhstan.
(3) The unmineable coal seams of Karagandy coalfields are ideal for CO_2 storage based on the limited available data on Kazakhstani coalfields. Furthermore, this coalfield shows good potential for CO_2-ECBM recovery.
(4) The proposed formula for CO_2 storage in coalfields may be utilized for tabular coal seams; however, it may extend to any other seam if the correct area of the seam is known.

This paper provides an essential and initial assessment of the CO_2 storage capacity of coal seams of Kazakhstani carboniferous coalfields. However, the same analogy may be used in Kazakhstan's remaining five Jurassic coalfields. Nevertheless, detailed experimental investigations of various parameters, e.g., vitrinite reflectance, proximate, and ultimate analysis, are warranted and significant for quantifying the rank and maturity of coal. The accurate measurement of the CO_2 adsorption capacity of coal using the high-pressure adsorption isotherm will give more insight into the CBM and ECBM recovery from the coalfields and the competitive adsorption process. One of the future works of this crucial study on carboniferous coal formations includes studying the fundamental properties of caprock.

Notably, this is the first study on CO_2 storage potential and a detailed geological review of the coal basins in the post-Soviet territory of Kazakhstan.

Acknowledgements The authors are thankful to Tongji University (2022YFC3003403) and Nazarbayev University, Kazakhstan (021220CRP2022) for their financial support.

References

Abuov Y, Seisenbayev N, Lee W (2020) CO_2 storage potential in sedimentary basins of Kazakhstan. Int J Greenh Gas Control 103:103186

Agency IE, (2022) Kazakhstan 2022 Energy sector review, energy sector review (ESR).

Ahuja M, Asif M, Mishra DP, Panigrahi DC, (2021) Modelling of CO_2-ECBM displacement of Jharia coalfield, India, In: 82nd EAGE Conference and Exhibition. Amsterdam, Netherland, pp. 1–5

Ammosov II, Burcev DN, Gorsky II, Ivanov GA, Kotlukov VA, Kuznecov IA, Lugovoy GI, Mironov KV, Molchanov II, Nekipelov BE, Pogrebnov NI, Geology of coal and black deposits (In Russian). 1973a. Book: Issue 5. Part 1. Moscow. pp.13–718

Ammosov II, Burcev DN, Gorsky II, Ivanov GA, Kotlukov VA, Kuznecov IA, Lugovoy GI, Mironov KV, Molchanov II, Nekipelov BE, Pogrebnov NI, Geology of coal and black deposits (In Russian). 1973b. Book: Issue 5. Part 2. Moscow. pp.13–718

Asif M, Naveen P, Ojha K, Panigrahi DC, (2018) Competitive adsorption in coal : an implementation of carbon dioxide storage technology in moira colliery, India, in: 80th EAGE Annual Conference and Exhibition. pp. 4–6.

Asif M, Naveen P, Panigrahi DC, Kumar S, Ojha K (2019a) Adsorption isotherms of CO_2–CH_4 binary mixture using IAST for optimized ECBM recovery from sub bituminous coals of Jharia coalfield: an experimental and modeling approach. Int J Coal Prep Util 39:403–420

Asif M, Naveen P, Panigrahi DC, Ojha K, (2017) Pore characterization of coal of jharia coalfield for coalbed methane using pore image analysis, In 79th EAGE Conference and Exhibition 2017. pp. 14–16.

Asif M, Naveen P, Panigrahi DC, Ojha K, Anwer SS, (2018) Multicomponent adsorption modelling for enhanced coalbed methane recovery from jharia coalfield using iterative method, In: 80th EAGE Conference and Exhibition. pp. 12–14.

Asif M, Panigrahi DC, Naveen P, Ojha K (2019b) Construction of high-pressure adsorption isotherm: a tool for predicting coalbed methane recovery from Jharia coalfield, India. Int J Min Sci Technol 29:765–769

Asif M, Panigrahi DC, Ojha K, (2021) CO_2 sequestration and ECBM recovery: a new approach for mitigating the effect of global warming, In 82nd EAGE Conference and Exhibition. Amsterdam, Netherland, pp. 1–5

Asif M, Pillalamarry M, Panigrahi DC, Naveen P, Ojha K, (2019c) Measurement of coalbed gas content of Indian coalfields : a statistical approach. Int J Oil, Gas Coal

Asif M, Wang L, Hazlett R, Serikov G, (2022a) IAST modelling of competitive adsorption, diffusion and thermodynamics for CO_2—ECBM process, In: SPE EuropEC. Madrid Spain, pp. 1–10.

Asif M, Wang L, Naveen P, Longinos SN, Hazlett R, Ojha K, Panigrahi DC (2024) Influence of competitive adsorption, diffusion, and dispersion of CH_4 and CO_2 gases during the CO_2-ECBM process. Fuel 15(358):130065

Asif M, Wang L, Panigrahi DC, Ojha K, Hazlett R (2022b) Integrated assessment of CO_2-ECBM potential in Jharia Coalfield. India Sci Rep 12:7533

Asif M, Wang L, Wang R, Wang H, Hazlett R (2022c) Mechanisms in CO_2 -enhanced coalbed methane recovery process. Adv Geo-Energy Res 6:531–534

Azizov TM, Vlasov YI, (2013) Coal and oil shale basins and deposits of Kazakhstan. Almaty pp 6–106.

Bachu S, Adams JJ, (2003) Sequestration of CO_2 in geological media in response to climate change : capacity of deep saline aquifers to sequester CO_2 in solution 44, 3151–3175.

Baines SJ, Worden RH (eds) (2004) Geological storage of carbon dioxide, speacial, e. Gological Society, London

Box SE, Syusyura B, Seltmann R, Creaser RA, Dolgopolova A, Zientek ML, (2012) Dzhezkazgan and associated sandstone copper deposits of the Chu-Sarysu Basin, Central Kazakhstan.

Bustin RM, Clarkson CR (1998) Geological controls on coalbed methane reservoir capacity and gas content. Int J Coal Geol 38:3–26

Carroll RE, Pashin JC, (2003) Relationship of sorption capacity to coal quality: CO_2 sequestration potetial of the Coalbed Methane Potential in the Black Warrior Basin, in: 18th Annual Meeting , TSOP. Washington, DC, pp. 1–11.

Cheng Y, Zhang X, Lu Z, jun Pan Z, Zeng M, Du X, Xiao S (2021) The effect of subcritical and supercritical CO_2 on the pore structure of bituminous coals. J Nat Gas Sci Eng 94:104132

De Silva PNK, Ranjith PG, Choi SK (2012) A study of methodologies for CO_2 storage capacity estimation of coal. Fuel 91:1–15

Daukeev SZh, Uzhkenov BS, Miletenko NV, Morozov AF, Leonov YuG, Futong W, Akhmedov NA, Abdyllayev EK, Murzagaziev SM, A O, Orifov AA, Zan A, (2002) Atlas of the lithology-paleogeographical, structural, palinspastic and geoenvironmental maps of Central Eurasia (In Russian).

Fan C, Elsworth D, Li S, Zhou L, Yang Z, Song Y (2019) Thermo-hydro-mechanical-chemical couplings controlling CH_4 production and CO_2 sequestration in enhanced coalbed methane recovery. Energy 173:1054–1077

Fan C, Yang L, Sun H, Luo M, Zhou L, Yang Z, Li S (2023) Recent advances and perspectives of CO_2-enhanced coalbed methane: experimental, modeling, and technological development. Energy Fuels 37:3371–3412

Fan N, Wang J, Deng C, Fan Y, Mu Y, Wang T (2020) Numerical study on enhancing coalbed methane recovery by injecting N_2/CO_2 mixtures and its geological significance. Energy Sci Eng 8:1104–1119

Fang Z, Li X, Hu H (2011) Gas mixture enhance coalbed methane recovery technology: pilot tests. Energy Proc 4:2144–2149

Fujioka M, Yamaguchi S, Nako M (2010) CO_2-ECBM field tests in the Ishikari coal basin of Japan. Int J Coal Geol 82:287–298

George Hall (2007) Carbon sequestration ATLAS of the United States and Canada, US Department of Energy: "National Energy Technology lanboratory".

Godec M, Koperna G, Gale J (2014) CO_2-ECBM: a review of its status and global potential. Energy Proc. 63:5858–5869

Goodman A, Hakala A, Bromhal G, Deel D, Rodosta T, Frailey S, Small M, Allen D, Romanov V, Fazio J, Huerta N, McIntyre D, Kutchko B, Guthrie G (2011) U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. Int J Green h Gas Control 5:952–965

Gunter WD, Mavor MJ, Robinson JR, (2005) CO_2 storage and enhanced methane production: field testing at Fenn-Big valley, alberta, canada, with application, in: 7th International Conference on Greenhouse Gas Control. Elsevier Science Ltd, Oxford, pp. 413–421

Han S, Sang S, Zhang J, Xiang W, Xu A, (2022) Assessment of CO_2 geological storage capacity based on adsorption isothermal experiments at various temperatures: a case study of No. 3 coal in the Qinshui Basin. Petroleum.

Huang Y, Zheng QP, Fan N, Aminian K (2014) Optimal scheduling for enhanced coal bed methane production through CO_2 injection. Appl Energy 113:1475–1483

IPCC (2018) Summary for Policymakers. Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels., Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.

Jikich SA, Bromhal GS, Sams WN, Gorucu FB, Ertekin T, Smith DH, (2004) Economics for enhanced coalbed methane (ECBM) and CO_2 sequestration with horizontal wells. SPE East Reg Meet

Junussov M, Mustapayeva S (2024) Preliminary XRF analysis of coal ash from jurassic and carboniferous coals at five Kazakh mines: industrial and environmental comparisons. Appl Sci 14(22):10586

Junussov M, Tarikhov F, Abildakhanov A, Zhanaidar D, Mekenbek G, Assambayeva A (2024) Mineralogical and elemental analysis of Kazakh coals from three mines: Preliminary insights from mode of occurrence to environmental impacts. Open Geosci 16(1):20220721

Khoyashov N, Serik G, Togay A, Abuov Y, Alibekov A, Lee W (2024) Development of carbon capture and storage (CCS) hubs in Kazakhstan. Int J Greenhouse Gas Control 138:104259

Kolawole F, Evenick JC (2023) Global distribution of geothermal gradients in sedimentary basins. Geosci Front 14:101685

Korobkin VV, Buslov MM (2011) Tectonics and geodynamics of the western Central Asian Fold Belt (Kazakhstan Paleozoides). Russ Geol Geophys 52:1600–1618

Korre A, Shi JQ, Imrie C, Grattoni C, Durucan S (2007) Coalbed methane reservoir data and simulator parameter uncertainty modelling for CO_2 storage performance assessment. Int J Greenh Gas Control 1:492–501

Kumar H, Elsworth D, Liu J, Pone D, Mathews JP (2012) Optimizing enhanced coalbed methane recovery for unhindered production and CO_2 injectivity. Int J Greenh Gas Control 11:86–97

Law D, van der Meer LGH, Gunter WD, (2002) Numerical simulator comparison study for enhanced coalbed methane recovery-processes, Part I: pure carbon dioxide injection, in: SPE (Ed.), SPE Gas Technology Symposium. Caligary, pp. 1–14.

Le TD, Ha QD, Panfilov I, Moyne C, (2020) Multiscale model for flow and transport in CO_2-enhanced coalbed methane recovery incorporating gas mixture adsorption effects. Adv Water Resour 144.

Li X, Fang ZM (2014) Current status and technical challenges of CO_2 storage in coal seams and enhanced coalbed methane recovery: an overview. Int J Coal Sci Technol 1:93–102

Liu S, Fang H, Sang S, Ashutosh T, Wu J, Zhang S, Zhang B (2020) CO_2 injectability and CH_4 recovery of the engineering test in Qinshui Basin, China based on numerical simulation. Int J Green h Gas Control 95:102980

Liu S, Liu T, Zheng S, Wang R, Sang S (2023) Evaluation of carbon dioxide geological sequestration potential in coal mining area. Int J Green h Gas Control 122:103814

Longinos SN, Longinou DD, Myrzakhmetova N, Akimbayeva N, Zhursumbaeva M, Abdiyev K, Toktarbay Z, Parlaktuna M (2022) Kinetic analysis of methane hydrate formation with butterfly turbine impellers. Molecules 27(14):4388

Longinos SN, Longinou DD, Parlaktuna M, Toktarbay Z (2021) The impact of methionine, tryptophan and proline on methane

(95%)–propane (5%) hydrate formation. React Kinet Mech Catal 134:653–664

Longinos SN, Parlaktuna M (2021) Examination of asparagine, aspartic acid and threonine in methane (95%)-propane (5%) gas hydrates as kinetic inhibitors. React Kinet Mech Catal 134:87–94

Lu P, Liu W, Gao C, Zhao J, Bai Y, (2021) Evaluation of carbon dioxide storage in the deep saline layer of the Ordovician Majiagou Formation in the Ordos Basin. In IOP conference series: earth and environmental science, Vol. 675, No. 1, p. 012058. IOP Publishing.

Ma T, Rutqvist J, Liu W, Zhu L, Kim K (2017) Modeling of CO_2 sequestration in coal seams: role of CO_2-induced coal softening on injectivity, storage efficiency and caprock deformation. Greenh Gases Sci Technol 7:352–368

Mazzotti M, Pini R, Storti G (2009) Enhanced coalbed methane recovery. J Supercrit Fluids 47:619–627

Van Der MB (2005) Carbon dioxide storage in natural gas reservoirs. Oil Gas Sci Technol 60:527–536

Mohammad SA, Sudibandriyo M, Fitzgerald JE, Liang X, Robinson RL, Gasem KAM (2012) Measurements and modeling of excess adsorption of pure and mixed gases on wet coals. Energy Fuels 26:2899–2910

Mohammadpoor M, Firouz AQ, Torabi F, (2012) Implementing simulation and artificial intelligence tools to optimize the performance of the CO_2 sequestration in coalbed methane reservoirs, in: Carbon Management Technology Conference. Orlando, Florida.

Mohanty D, Chattaraj S, Singh AK (2018) Influence of coal composition and maturity on methane storage capacity of coals of Raniganj Coalfield. India Int J Coal Geol 196:1–18

Muhammed NS, Haq B, Al Shehri D, Al-Ahmed A, Rahman MM, Zaman E (2022) A review on underground hydrogen storage: insight into geological sites, influencing factors and future outlook. Energy Rep 8:461–499

Mukherjee M, Misra S (2018) A review of experimental research on Enhanced Coal Bed Methane (ECBM) recovery via CO_2 sequestration. Earth-Science Rev 179:392–410

National inventory report, 2016. Kazakhstan cliamte facts and policy. https://zoinet.org/wp-content/uploads/2018/02/CC-Kazakhstan-web-2016.pdf Accessed Aug 2023)

Naveen P, Asif M, Ojha K, Panigrahi DC, Vuthaluru HB (2017) Sorption kinetics of CH_4 and CO_2 diffusion in coal: theoretical and experimental study. Energy Fuels 31:6825–6837

Norouzbahari S, Shahhosseini S, Ghaemi A (2015) Modeling of CO_2 loading in aqueous solutions of piperazine: application of an enhanced artificial neural network algorithm. J Nat Gas Sci Eng 24:18–25

Ojha K, Karmakar B, Mandal A, Pathak AK (2011) Coal Bed methane in India: difficulties and prospects. Int J Chem Eng Appl 2:256–260

Ottiger S, Pini R, Storti G, Mazzotti M (2008) Competitive adsorption equilibria of CO_2 and CH_4 on dry coal. Adsorption 14:539–556

Pagnier H, van Bergen F, Krzystolik P, Skiba J, Jura B, Hadro J, Wentink P, De-Smedt G, Kretzschmar H-J, Fröbel J, Müller-Syring G, Krooss B, Busch A, Wolf K-H, Mazumder S, Bossie-Codreanu D, Choi X, Grabowski D, Hurtevent D, Gale J, Winthaegen P, van der Meer B, Kobiela Z, Bruining H, Reeves S, Stevens S, (2005) Field experiment of ECBM-CO2 in the Upper Silesian Basin of Poland (RECOPOL), 7th International Conference on Greenhouse Gas Control. Elsevier Science Ltd, Oxford, pp. 1391–1397.

Pan Z, Ye J, Zhou F, Tan Y, Connell LD, Fan J (2018) CO_2 storage in coal to enhance coalbed methane recovery: a review of field experiments in China. Int Geol Rev 60:754–776

Pashin JC, Mcintyre MR, (2003) Temperature—pressure conditions in coalbed methane reservoirs of the Black Warrior basin : implications for carbon sequestration and enhanced coalbed methane recovery 54, 167–183.

Perera MSA, (2014) Investigation of the effect of carbon dioxide sequestration on coal seams: a coupled hydro-mechanical behavior. Thesis Summary for Rocha Medal

Perera MSA, Ranjith PG, Airey DW, Choi SK (2011) Sub- and super-critical carbon dioxide flow behavior in naturally fractured black coal : an experimental study. Fuel 90:3390–3397

Perera MSA, Ranjith PG, Choi SK, Airey D, Weniger P (2012) Estimation of gas adsorption capacity in coal: a review and an analytical study. Int J Coal Prep Util 32:25–55

Perera MSA, Ranjith PG, Choi SK, Bouazza A (2013) A parametric study of coal mass and cap rock behaviour and carbon dioxide flow during and after carbon dioxide injection. Fuel 106:129–138

Pini R, Storti G, Mazzotti M (2011) A model for enhanced coal bed methane recovery aimed at carbon dioxide storage: the role of sorption, swelling and composition of injected gas. Adsorption 17:889–900

Ranathunga AS, Perera MSA, Ranjith PG, Wei CH (2017) An experimental investigation of the applicability of CO_2 enhanced coal bed methane recovery to low-rank coal. Fuel 189:391–399

Reeves S, Taillefert A, (2003) The Allison Unit CO_2—ECBM pilot : a reservoir modeling study topical report. U.S. Department of Energy Award Number DE-FC26-0NT40924

Rowley DB, Raymond A, Parrish JT, Lottes AL, Scotese CR, Zeigler AM (1985) Carboniferous paleogeographic, phytogeographic, and paleoclimatic reconstructions. Int J Coal Geol 5:7–42

Sabitova DK (2015) Exploration potential of coalbed methane in Karaganda field. Mod Appl Sci 9:145–159

Sayyafzadeh M, Keshavarz A (2016) Optimisation of gas mixture injection for enhanced coalbed methane recovery using a parallel genetic algorithm. J Nat Gas Sci Eng 33:942–953

Sayyafzadeh M, Keshavarz A, Alias ARM, Dong KA, Manser M (2015) Investigation of varying-composition gas injection for coalbed methane recovery enhancement: a simulation-based study. J Nat Gas Sci Eng 27:1205–1212

Seidle J, (2000) Reservoir engineering aspects of CO_2 sequestration in coals. in: SPE/CERI gas technology symposium. Calgary, Alberta, Canada

Serikov G, Wang L, Asif M, Hazlett R, (2022) Simulation evaluation of CO_2-ECBM potential in Karaganda coal basin in Kazakhstan, in: SPE EuropEC. Madrid Spain.

Shi JQ, Durucan S, (2008) Modeling of mixed-gas adsorption and diffusion in coalbed reservoirs. SPE Unconv Reserv Conf 10–12.

Shi JQ, Durucan S (2005) CO_2 storage in deep unminable coal seams. Oil Gas Sci Technol 60:547–558

Shimada S, Li H, Oshima Y, Adachi K (2005) Displacement behavior of CH_4 adsorbed on coals by injecting pure CO_2, N_2, and CO_2-N_2 mixture. Environ Geol 49:44–52

Stevens SH, Spector D, Riemer P, (1998) Enhanced coalbed methane recovery using CO_2 injection: worldwide resource and CO_2 sequestration potential, in: SPE international oil and gas conference and exhibition in China. Society of Petroleum Engineers, Neijing, China, p. SPE 48881.

Tiyntayev Y, Tursymat O, Serikov G, Asif M, Wang L, Hazlett R, (2022) Simulation-based evaluation of concurrent CH_4 storage potentials during CO_2-ECBM in Karaganda coal basin. SPE Annu Casp Tech Conf

United Nations S-G, (2019) Report of the secretary-general on the 2019 Climate Action Summit and the way forward in 2020. United Nations.

Vandamme M, Brochard L, Lecampion B, Coussy O (2010) Adsorption and strain: the CO_2-induced swelling of coal. J Mech Phys Solids 58:1489–1505

Vishal V (2017) In-situ disposal of CO_2: liquid and supercritical CO_2 permeability in coal at multiple down-hole stress conditions. J CO2 Util 17:235–242

Vishal V, Mahanta B, Pradhan SP, Singh TN, Ranjith PG (2018) Simulation of CO_2 enhanced coalbed methane recovery in Jharia coalfields, India. Energy 159:1185–1194

Vishal V, Singh L, Pradhan SP, Singh TN, Ranjith PG (2013) Numerical modeling of Gondwana coal seams in India as coalbed methane reservoirs substituted for carbon dioxide sequestration. Energy 49:384–394

Vishal V, Singh TN (2016) Geologic carbon sequestration: understanding reservoir behaviour. Springer International Publishing AG, Switzerland

Vishal V, Singh TN, Ranjith PG (2015) Influence of sorption time in CO_2-ECBM process in Indian coals using coupled numerical simulation. Fuel 139:51–58

WBG (2016) World bank group climate change action plan 2016–2020. World Bank Gr. 74.

Wei G, Wen H, Deng J, Ma L, Li Z, Lei C, Fan S, Liu Y, (2021) Liquid CO_2 injection to enhance coalbed methane recovery: an experiment and in-situ application test. Fuel 284.

Wei X, Massarotto P, Wang G, Rudolph V, Golding SD (2010) CO2 sequestration in coals and enhanced coalbed methane recovery: new numerical approach. Fuel 89:1110–1118

Wei X, Wang G, Massarotto P, Golding S, (2006) A case study on the numerical simulation of enhanced coalbed methane recovery 1–6.

Wei XR, Wang GGX, Massarotto P, Golding SD, Rudolph V (2007) A review on recent advances in the numerical simulation for the coalbed-methane-recovery process. SPE Reserv Eval Eng 10:657–666

White CM, Smith DH, Jones KL, Goodman AL, Jikich SA, Lacount RB, Dubose SB, Ozdemir E, Morsi BI, Schroeder KT (2005) Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery: a review. Energy Fuels 19:659

Yang Y, Clarkson CR, Hamdi H, Ghanizadeh A, Blinderman MS, Evans C (2023) Field pilot testing and reservoir simulation to evaluate processes controlling CO_2 injection and associated in-situ fluid migration in deep coal. Int J Coal Geol 275:104317

Yu H, Jing R, Wang P, Chen L, Yang Y (2014) Preferential adsorption behaviour of CH_4 and CO_2 on high-rank coal from Qinshui Basin. China Int J Min Sci Technol 24:491–497

Zeng Q, Wang Z, Liu L, Ye J, Mcpherson BJ, Mclennan JD (2018) Modeling CH_4 displacement by CO_2 in deformed coalbeds during enhanced coalbed methane recovery. Energy Fuels 32:1942

Zhang C, Wang E, Li B, Kong X, Xu J, Peng S, Chen Y (2023) Laboratory experiments of CO_2-enhanced coalbed methane recovery considering CO_2 sequestration in a coal seam. Energy 262:125473

Zhang K, Cheng Y, Jin K, Guo H, Liu Q, Dong J, Li W (2017) Effects of supercritical CO2 fluids on pore morphology of coal: implications for CO_2 geological sequestration. Energy Fuels 31:4731–4741

Zhang L, Ren T, Aziz N (2014) Influences of temperature and moisture on coal sorption characteristics of a bituminous coal from the Sydney Basin, Australia. Int J Oil Gas Coal Technol 8:62–78

Zhang Y, Lebedev M, Sarmadivaleh M, Barifcani A, Iglauer S (2016) Swelling-induced changes in coal microstructure due to supercritical CO_2 injection. Geophys Res Lett 43:9077–9083

Zhao W, Su X, Xia D, Hou S, Wang Q, Zhou Y (2022) Enhanced coalbed methane recovery by the modification of coal reservoir under the supercritical CO_2 extraction and anaerobic digestion. Energy 259:124914

Zheng S, Yao Y, Elsworth D, Liu D, Cai Y (2020) Dynamic fluid interactions during CO2-enhanced coalbed methane and CO_2 sequestration in coal seams. Part 1: CO_2-CH_4 interactions. Energy Fuels 34:8274–8282