Introduction

Climate change has intensified over recent decades, manifesting as extreme weather events, rising temperatures, and environmental devastation. Since the Industrial Revolution, fossil fuel consumption has led to a surge in greenhouse gas emissions, with CO_2 contributing 76% of global emissions. Atmospheric CO_2 levels have risen from 280 ppm (1880) to 425 ppm (2024), driving global temperatures up by 1.07°C. In response, the 2015 Paris Agreement set a goal to limit warming below 1.5°C.

While afforestation, renewable energy expansion, and energy efficiency improvements aid CO_2 mitigation, these alone are insufficient to achieve net-zero emissions by 2050. Geological carbon sequestration is a viable long-term solution, with significant investments driving technology advancements. Potential storage sites include depleted oil reservoirs, saline aquifers, and unconventional gas reservoirs. Among these, Enhanced Coalbed Methane (ECBM) recovery offers a triple advantage—storing CO_2 in coal seams, extracting methane (CBM) as a fuel source, and enhancing mine safety by reducing methane buildup. public and private investments in CO_2 geo-sequestration technologies are growing, reinforcing its potential as a key strategy in achieving sustainable energy solutions and long-term climate stability.

Method

For this study, coal samples were collected from various mines in the Jharia coalfield, India. Proximate and ultimate analyses were conducted to determine the elemental composition. Adsorption isotherms were measured at 30°C, with moisture-equilibrated samples (96–97% relative humidity) prepared per ASTM D1412/D1412M standards to simulate reservoir conditions.

Gas adsorption volumes were calculated using the mass balance equation, real gas law, and equation of state. Isotherm measurements included 9 pressure steps (1000 KPa each) for CH_4 and 7 steps (1000 KPa each) for CO_2. Pressure drop data was recorded at 1-second intervals and analyzed using the Unipore and modified Unipore models to evaluate adsorption kinetics. To ensure equilibrium, a 12-hour interval was maintained between successive pressure steps for both CH_4 and CO_2 isotherms.

Conclusions

The results of the proximate analysis show that the coals fixed carbon content ranges from 77.2 to 79.1 % (pdf), and it is linearly increasing from upper (shallow depth) to lower seams (higher depth). The result of the ultimate analysis reveals that the samples exhibit high carbon content, varying within the range 86.5-91.7% (dmmf). The Langmuir volume (daf basis) for CH4 isotherm varies in a comparatively narrow range as compared to CO2 isotherm. It ranges between 19.4-23.8cc/g and 26.6-43.6cc/g (daf) for CH4 and CO2 respectively (Table 1). For both the gases Langmuir volume is higher for upper seam coals. The daf-wise ratio of Langmuir volume between CH4 and CO2 varies between 1:1.37 to 1:1.83The Langmuir pressure for CH4 and CO2 varies between 1608-3646 KPa and 1294-3123KPa respectively.

Table 1: Results of adsorption isotherm construction for Jharia Coals

Sample ID	$V_{L\ daf}$		$P_{L,\ KPa}$	Eq. Moisture (%)	Density (g/cc)
	CH_4	CO_2			
ICJ-1	23.8	43.6	1294	1.33	1.27
ICJ-2	22.5	35.4	1975	1.45	1.39
ICJ-3	23.4	38.8	1217	1.31	1.30
ICJ-4	20.0	29.2	3075	1.06	1.51
ICJ-5	19.4	26.6	3123	1.08	1.52

The depicted adsorption kinetic curve obtained from experimental adsorption resembles a Type I isotherm curve in terms of shape, which increases linearly at the early stage of adsorption, and the curve

flattens a bit with time. The experimental adsorption kinetic plots [fractional uptake (Vt/V∞) versus time (t0.5)] of two representative samples of the studied coals are shown in Figure 1.

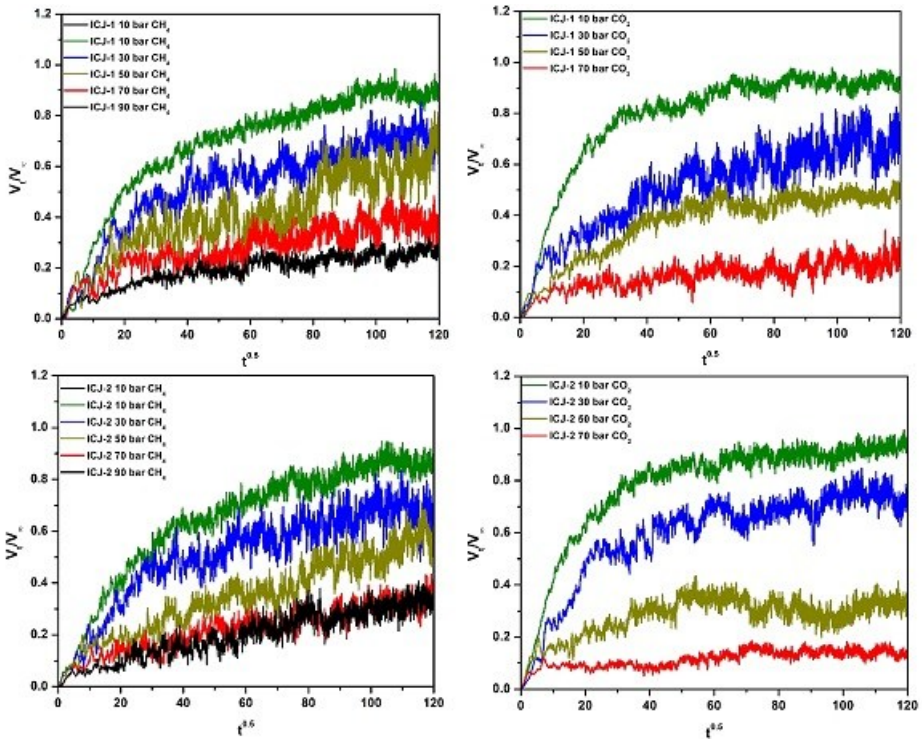

Figure 1: CH_4 and CO_2 sorption kinetic plots of ICJ-1 and ICJ-2 samples

The kinetic plots show that for all coal samples, the rate curve for CO2 adsorption is steeper at the initial stage, i.e., after the gas is injected into sample cells. However, CO2 takes comparatively less time to reach equilibrium than methane. The slope of the adsorption kinetic plots is determined in order to calculate the precise sorption kinetic rate. A clearly decreasing trend of the slope with the increase in pressure has been observed for both gases, which depicts that the sorption rate has a strong dependency on the pressure. It also depicts that in the initial stage, the adsorption rate is faster due to the availability of a large number of vacant sites. The driving force and the number of available sites decline with the increased contact time. Moreover, adsorbate molecules in the sorbed and bulk phases inhibit each other as the stage approaches equilibrium. The comparatively slower kinetics of CO2 at higher pressure is also attributed to the swelling that occurs during gas injection, which inhibits the CO_2 storage and release of CH_4.

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