Geotechnical Review of Geological CO_2 Sequestration

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Abstract:

Geological CO_2 sequestration offers a promising method for mitigating climate change by storing carbon dioxide in subsurface formations. This concise review highlights key geotechnical aspects, focusing on the selection and characterization of suitable sites, such as deep saline aquifers, depleted oil and gas fields, and unmineable coal seams. Essential factors like injectivity, capacity, and effectiveness are quantitatively evaluated to determine their feasibility for CO_2 storage. Geotechnical considerations include the analysis of pore pressure, in-situ stresses, and rock strength, ensuring the stability and integrity of storage sites. Advanced techniques for monitoring and verifying storage sites are covered, alongside modeling approaches to predict long-term CO_2 behavior. Risk assessment addresses potential hazards such as leakage and induced seismicity, with strategies for mitigation discussed. Brief case studies provide practical examples of successful CO_2 sequestration projects, illustrating their geotechnical attributes. The paper identifies key geotechnical properties such as high porosity and permeability, favorable cap rock integrity, and robust geomechanical stability as essential for improving CO_2 sequestration efficiency and safety. The potential for geological CO_2 sequestration in Pakistan is also briefly examined, highlighting opportunities in local geological formations. Future recommendations put emphasis on the need for improved characterization techniques and robust monitoring systems to ensure the long-term viability of geological CO_2 storage. This review underscores the critical role of precise geotechnical evaluations in facilitating effective CO_2 sequestration, essential for addressing global climate challenges.

Keywords: Geological CO_2 sequestration, Geotechnical engineering, Site characterization, Carbon storage

1. Introduction:

A significant increase in greenhouse gases, such as CO_2 and CH_4, has occurred since the Industrial Transformation, causing global warming and environmental problems. Among all the greenhouse gases CO_2 accounts for 64% of the greater greenhouse effect due to its high quantity compared to other greenhouse gases [1]. Burning fossil fuels like oil, gas, and coal to meet our energy needs has rapidly released CO_2 into the atmosphere at a much faster rate [2]. The biggest challenge in minimizing the effects of human-caused climate change is lowering CO_2 emissions in the atmosphere. Various efforts are being made to reduce the emissions of CO_2, among which Geological CO_2 Sequestration has emerged as a promising method for long-term and safe storage of CO_2.

The process of directly extracting CO2 from the atmosphere or an industrial source and storing it in a biological or geological reservoir in order to lower its concentration in the atmosphere and enhance climate conditions is known as sequestration. Geological CO_2 Sequestration involves the storage of CO_2 in geological formations such as depleted oil and gas reservoirs, saline aquifers, coal mines, and other rock formations [3]. Geological CO_2 sequestration was developed in the late 20th century as a solution to the pressing requirement of reducing the impact of climate change. Preliminary studies emphasized the possibility of storing captured carbon dioxide in geological structures, particularly in depleted oil and gas fields and deep saline aquifers [4]. The development of Enhanced Oil Recovery (EOR) techniques in the 1970s demonstrated the feasibility of CO_2 injection for oil recovery, leading to the realization that this process could also function as a means for long-term CO_2 storage [5][6]. With the development of monitoring technology and regulatory frameworks over time, geological sequestration has gained credibility and become an essential part of Carbon Capture, Utilization, and Storage (CCUS) devices [7]. ***Figure 1*** displays the different steps involved in the process of CO_2 Capture and Storage.

The utilization of CO_2 in addressing engineering issues presents significant potential for widespread adoption in mitigating greenhouse gas emissions. However, the intricate changes that carbonation causes to the soil's physical, chemical, mechanical, deformation, and durability qualities present difficulties for potential engineering applications [8]. There is a need to examine geological CO_2 sequestration from a geotechnical perspective for safe, stable, effective, and long-term CO_2 storage. The geotechnical elements of geological CO2 sequestration (CCS) are thoroughly reviewed in this paper, focusing on the properties and behavior of supercritical CO_2, suitable geological formations, and key geotechnical challenges such as site selection, injection techniques, and monitoring to assess and mitigate risks associated with CO_2 injection, such as leakage, ground deformation, and induced seismicity, thus ensuring that the CO_2 remains securely trapped underground.

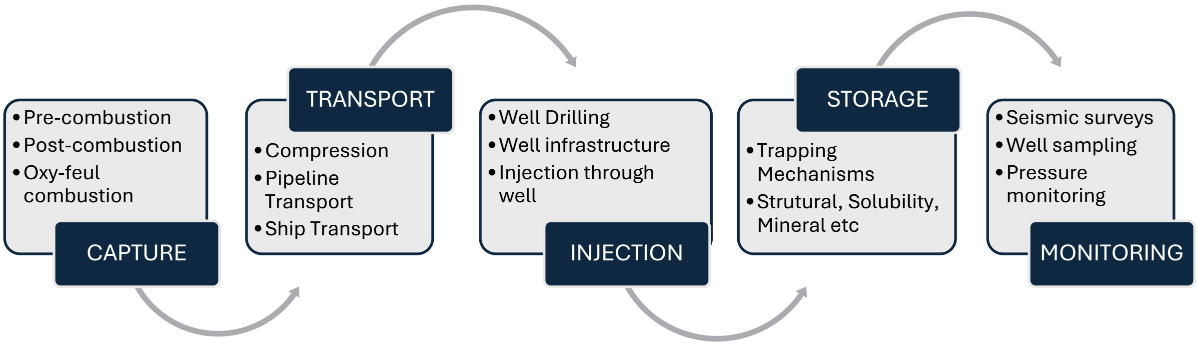

Figure 1: CO2 Sequestration Process

2. Geological CO_2 Sequestration:

2.1 Geological Formations:

CO_2 is a stable gas under normal conditions but becomes a non-polar, supercritical fluid above 31.1°C and 7.38 MPa, making it insoluble in water and a good solvent for organic compounds. Over 800 meters of depth is typically the depth at which this state occurs [9]. For CO_2 to be in the supercritical state, critical values of pressure and temperature are required which is typically the case in most sequestration reservoirs. In selecting suitable techniques and sites to dispose of and sequester CO_2, all these factors must be taken into account [10]. Following are the major potential geological formations that can encompass CO_2 Sequestration:

Depleted Oil and Gas Reservoirs: Reservoirs that have generated most of their oil and gas are depleted. These reservoirs contain hydrocarbons but are no longer economically viable for traditional extraction.

Deep Saline Aquifers: Subsurface layers of water-bearing rock, sediment, or soil with high dissolved salt concentrations.

Deep Coal Seams: These formations are commonly referred to as unmineable coal seams. They consist of organic minerals and contain brine and gases inside their pore and fracture volumes [11].

Table 1: Storage Capacity of different Geological Formations [3], [11]

Formation Type	**Storage Capacity**
Depleted Oil Reservoirs	150-700 (Gt)
Depleted Gas Reservoirs	500-1100 (Gt)
Deep Saline Aquifers	320-10000 (Gt)
Unmineable Coal Seams	10-1000 (Gt)

Geological formations in the subsurface have a long history of retaining oil, gas, and water thanks to their impermeable cap rock layer, making them optimal for the storage of CO_2 [12]. Depleted oil and gas reservoirs are suitable for CO_2 storage because they already have sealed layers, infrastructure, and prior experience with CO_2 injections. Despite having a lesser storage capacity than saline aquifers, they offer a safer and more established alternative for CO_2 sequestration. Gas reservoirs, specifically, present a higher capacity for storing CO_2. Moreover, the utilization of these reservoirs can effectively decrease the release of greenhouse gases while also improving the process of extracting oil [13][14]. Because of their large availability in sedimentary basins and high storage capacity (up to 10,000 Gt CO_2), deep saline aquifers are considered the most practical option for sequestering CO_2. Because of their high porosity and permeability, they are able to withhold pressure and injection effectively. Moreover, these aquifers are extensively distributed, not fit for consumption, and easily available from numerous CO_2 capture locations, hence, improving both cost-effectiveness and environmental security [15][16]. In contrast to hydrodynamic entrapment in aquifers, un-mineable coal seams provide a potential reservoir for CO_2 sequestration through adsorption on coal micropores [17]. Displacement of adsorbed methane by injected CO_2 can improve coal bed methane recovery (CBM) [18]. This could make abandoned coal seams useful for energy production, sequestering CO_2 and improving CBM extraction efficiency simultaneously [19]. Other formations include Basalt Formations, Oil Shale Formations, Ultramafic Rocks, Mined Salt Domes, and Rock Caverns. Basalt formations and ultramafic rocks, which facilitate CO_2 mineralization, are still experimental [20][21]. Oil shale and salt caverns appear promising storage formations but are still mostly under research [22][23]. ***Table 1*** gives the storage capacity of the various geological formations discussed.

2.2 Storage Mechanisms:

The dispersion of CO_2 inside a reservoir is influenced by multiple factors that come into play at different stages of the CO_2 mitigation process. Effective long-term storage is dependent upon the interaction of these trapping mechanisms. The injected supercritical CO_2 is securely trapped by three main trapping mechanisms (physical trapping, chemical trapping, and physicochemical trapping). Effective long-term storage is dependent upon the interaction of these trapping mechanisms [23]

Physical trapping allows CO_2 to retain its characteristics after being injected into an aquifer [23]. This includes structural trapping, where geological formations like anticlines with cap rocks hold CO_2 as a supercritical fluid. Viscous forces assist CO_2 migration during injection, while buoyancy pushes it upward until it encounters impermeable structures [23][24]. Structural trapping is often the most effective during the early stages of CO_2 injection but also plays a crucial role in long-term storage by preventing leakage. It was the dominant mechanism in the Sleipner Project located in the North Sea, Norway, and involves CO_2 storage in the Utsira Formation, a saline aquifer. During the first 12 years of injection, 70% of CO2 was stored on account of structural trapping. The formation consists of sandstone, with a shale caprock network effectively sealing the CO_2 and preventing upward migration [25][26]. Residual or capillary trapping occurs when some CO_2 is trapped in pore spaces by capillary forces, thereby improving stability over the long term [24][27][28]. Residual trapping plays a significant role in both the initial and later stages of CO_2 storage. During the early injection phase, capillary forces trap CO_2 in small pores, helping to secure the CO_2. Over time, residual trapping continues to prevent CO_2 migration, ensuring long-term containment. This mechanism has been crucial in various projects, including the Otway Project in Victoria, Australia. In Otway, residual CO_2 saturation was measured at 18% in the lower perforated interval and 23% in the upper interval, confirming its effectiveness for stable, long-term CO_2 storage [29].

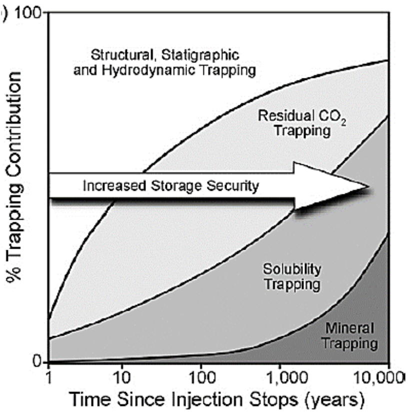

Figure 2: Trapping mechanisms over time [4]

Chemical trapping involves interactions between CO_2 and the brine and rock in the formation, leading to chemical alterations that enhance storage capacity [23]. This includes solubility trapping, where CO_2 dissolves in brine, increasing its density and reducing buoyancy effects. Although the dissolution process is slow, it plays a significant role in enhancing storage capacity [27]. In the SACROC (Scurry Area Canyon Reef Operators Committee) Northern Platform case study, 1.7 million metric tons of CO_2 were trapped in brine by the end of injection, rising to 2.3 million metric tons over 200 years post-injection. This accounted for 30–35% of total CO_2 storage, demonstrating its significant contribution across both injection and post-injection phases [30]. The process of mineral entrapment entails the interaction of CO_2 with the minerals present in the formation, leading to the gradual creation of stable carbonate minerals. In the CarbFix method, conducted in basaltic formations in Iceland, nearly all injected CO_2 mineralized within 8–10 years due to basalt's high reactivity. In contrast, large-scale simulations for sedimentary reservoirs showed mineralization ranging from 17% to 60% over 150 years, depending on geochemical conditions [31]. CO_2 can be sequestered more permanently through this process, but the conditions of formation and the mineralogy of the rock affect this process' effectiveness [24][27][28][32].

Chemical and physical storage mechanisms are linked by physicochemical trapping, mainly through hydrodynamic trapping [23]. Physicochemical trapping refers to the process where CO_2 is trapped in a reservoir through a combination of physical and chemical interactions. It is the combined action of several trapping mechanisms—structural trapping, residual trapping, solubility trapping, and mineral trapping—that work together to securely store CO_2 in a reservoir. Hydrodynamic trapping refers to the trapping of CO_2 in a reservoir as a result of slow fluid movement. As CO_2 is injected, it migrates upwards and can be held by various mechanisms, such as residual trapping, solubility trapping, or mineral trapping, depending on fluid flow and formation characteristics [23][27][33]. ***Figure 2*** shows the contribution of different trapping mechanisms over time.

3. Geotechnical Considerations:

In the context of geological CO_2 sequestration, geotechnical considerations are critical to guarantee the stability, safety, and success of the storage site. This section delves into the key geotechnical factors that must be addressed for successful CO_2 sequestration.

3.1 Site Selection and Characterization:

The success of CO_2 storage projects depends heavily on selecting suitable sites, which requires a detailed assessment of geological structure, safety, storage potential, and suitability. Proper site characterization minimizes risks and enhances project success, serving the interests of all stakeholders [34]. Site characterization criteria have been defined differently by different researchers, but they carry the same concept.

S. Julio Friedmann identified three key geological criteria for effective CO_2 sequestration: targets, seals, and appropriate subsurface conditions. Targets, or reservoirs, are porous and permeable geological units, such as sandstones or limestones, that can hold large volumes of CO_2. Seals, or cap rocks, are impermeable layers like shales or evaporites that prevent upward CO_2 migration. In addition, CO_2 should be injected deeper than 800 m to maintain a supercritical, dense phase, optimizing storage capacity [33]. Stefan Bachu noted that the CO_2 sequestration site selection process starts with assessing the suitability of sedimentary basins on a regional scale. This evaluation involves fixed basin characteristics like tectonics and geology, along with evolving basin resources such as hydrocarbons, coal, salt, and infrastructure. Lastly, societal factors, including economic conditions and public perception, can vary widely [35]. In another study, Bachu defined the essential characteristics of geological media for CO_2 storage as the capacity to store CO_2. Second is the capability to take in the CO_2 being injected at a maintained rate and store it safely and effectively (injectivity), for managing injection rates, and thirdly, confinement to inhibit movement or leakage. Sedimentary basins, especially sandstone and carbonate rocks, meet these requirements, while less pervious shales and evaporites serve as barriers. Coal can also adsorb CO_2, but crystalline, metamorphic, and volcanic rocks typically lack the necessary properties, although research is exploring basalts as a potential option [36][24]. Another proposed evaluation criteria include four components: location and geological settings, injectivity factors (mineralogy, porosity, permeability, and stratigraphy), sealing capability (sealing probability, CO_2 movement, fault stability, and pore pressure), and overall storage capacity. Furthermore, one study highlighted that evaluating storage capacity, injectivity, trapping mechanisms, and reservoir seal strength using numerical and laboratory approaches is crucial. Identification of advantageous CO_2 storage zones requires a thorough injectivity review guided by facies and petrophysical descriptions. [37]. According to another study, factors to consider when selecting a saline layer include seismic activity, volcanic activity, and the presence of fractures, as well as the porosity and permeability characteristics [38]. ***Table 2*** highlights key parameters for assessing the suitability of zones for geological CO_2 sequestration.

Table 2: The suggested metrics indicate the optimal zones for efficient CO_2 storage [37]

Parameters	**Positive Indicators**	**Aspect Indication**
Depth	>800m	Storage capacity
CO2 Density	high	Storage capacity
Porosity	>20%	Storage capacity
Thickness	>>50m	Injectivity
Permeability (near wellbore)	>100mD	Injectivity
Size distribution of pore throat	less heterogenous	Injectivity
Saturation of residual gas/water	low	Injectivity
Saturation of Condensate (oil phase)	low	Injectivity
Lithofacies type	good quality	Injectivity

3.2 Assessing Parameters – Injectivity, Capacity and Effectiveness:

In CO_2 sequestration, injectivity refers to the ability of a geological formation to accept and store injected CO_2 at a given pressure and rate. It is the injection rate/difference of pressure between the reservoir and the well. It is a critical factor in determining how efficiently CO_2 can be injected into the reservoir without causing unwanted pressure buildup or compromising the formation's integrity. Different factors that influence injectivity are rock mineralogy, pore water chemistry, pressure, temperature, and CO_2 flow rate [39]. Water-rock-CO_2 interactions can change injectivity over time, so these interactions must be considered when selecting a storage site. The capacity of a site is constrained by pressure buildup during CO_2 injection, which is directly connected to injectivity. Shallow sites having low permeability and high porosity are often more pressure constrained. Short injection times further exacerbate this constraint, leading to rapid pressure increases [40]. As part of the injection of CO2 and the post-injection stage, several physical processes are involved. During injection, viscous forces dominate the migration of CO_2, while buoyancy and capillary forces play key roles in trapping CO_2 post-injection. Migration leads to a hysteresis effect, critical for modeling CO_2 trapping processes, resulting in disconnected CO_2 blobs trapped in the formation, which may eventually dissolve in the formation brine [24].

Capacity measures the total volume of potential CO_2 storage in formation, constrained by pore volume, formation thickness, and porosity. Estimations rely on well data, geological surveys, and occasionally 3D seismic surveys [39]. There are two main estimation methods: static, which uses fixed properties, and dynamic, which incorporates time-dependent variables. Different formations require distinct approaches, and uncertainties arise from heterogeneity and trapping mechanisms. Key methodologies include those from the U.S. Department of Energy and the Carbon Sequestration Leadership Forum [24]. Most evaluations use volumetric methods that consider pore space, adjusted for pressure effects and brine distribution while new methods are being developed as shown in ***Table 3***.

Effectiveness refers to a geological formation's ability to securely contain injected carbon dioxide over the long term. It relies on the integrity of cap rocks and sealing units to prevent CO_2 migration. Key factors include geomechanical properties, hydrodynamic behavior, and fault integrity. While precise estimates can be difficult, site characterization through seismic surveys and geological data provides valuable insights into the expected performance of CO_2 storage sites [39].

Table 3: Various methods for estimating CO_2 capacity (modified from [41]

Method	**Reservoir**	**Trapping Mechanism**	**Equation/ Model**	**Reference**
CSLF	Oil	Structural	$G_t = \rho_{CO_2}\left[\frac{R_f\,OGIP}{B_f} - V_{iw} + V_{pw}\right]$	[41] [28]
	Gas		$G_t = \rho_{CO_2} R_f (1 - F_{IG}) OGIP \left[\frac{P_s Z_r T_r}{P_r Z_s T_s}\right]$	
	Oil & Gas		$G_t = \rho_{CO_2}\left[R_f Ah\varphi(1 - S_w) - V_{wi} + V_{wp}\right]$	
	Coal		$G_e = \rho_{CO_2 std} IGIP\ R_f C'$	
	Saline Aquifer		$G_e = Ah\varphi\rho_{CO_2}(1 - S_{wirr})C_c$	
		Solubility	$G_e = Ah\varphi\left(\rho_{w_s} X_s^{CO_2} - \rho_{w_0} X_0^{CO_2}\right)C$	
		Residual	$G_t = \Delta V_{trap}\rho_{CO_2}\varphi S_{{CO_2}_{trap}}$	
USDOE	Oil & gas	Structural	$G_e = AH_{\varphi_e}(1 - S_w)B_f\rho_{{CO_2}_{std}}E$	
	Saline aquifer		$G_e = Ah\varphi\rho_{CO_2}E$	
	Coal		$G_e = Ah\ C\ \rho_{CO_2 std}E$	
USGS	Saline aquifer	Buoyant & Residual	$G_{tech} = \rho_{CO_2} V_b E_b + \sum_{i=1}^{3}\left[\rho_g(AH\varphi - V_b)R_i R_w E_r\right]$	
Pressure limit method	Saline Aquifer	Compressibility	$G_e(t_i) = Ah\varphi\rho_{CO_2}E$	

Numerical Simulation	Coal	Adsorption & Displacement	$G_t = \left(\frac{0.1 \times Ah\rho_{coal}G_cR_f\, ER\, \rho_{CO_2std}}{10^6}\right) + \left[Ah\varphi(1 - S_W)(1 - R_W)m_{CO_2water}\right] + \left(Ah\varphi S_W R_w \rho_{CO_2}\right)$	
IEA-GHG	Gas	Structural	$G_e = URRgas_{std}B_f\rho_{CO_2}\, E$	
Lattice Boltzmann	General	Structural & Residual	Pore Scale, Lattice Boltzmann Equation	[42]
PFLOTRAN	Fractured	Mineral & Solubility	Reactive Trasport Model (Multi-phase Flow Equation	[43] [44]
TOUGH2, CMG, GEM	Depleted Oil & Gas	Structural, Residual & Mineral	Darcy's Law, Mass Conversion Equation	[45]
Machine Learning	Saline Aquifer	Structural, Residual & Solubility	Artificial Neural Networks (ANNs), Random Forest (RF), Support Vector Machines (SVM),	[46]

3.3 Monitoring, Verification, and Risk Management:

CO_2 Monitoring, Verification, and Accounting (MVA) technologies play a critical role in assuring the safety and efficacy of CO_2 storage. These methods are divided into atmospheric, near-surface, subsurface tools, and data integration systems [24][47]. Atmospheric monitoring tools, like CO_2 detectors, LIDAR, and eddy covariance, track CO_2 levels to ensure there are no atmospheric leaks. Near-surface tools, such as seismic surveys, InSAR, and tiltmeters, monitor groundwater, soil gas, and potential leaks between subsurface and atmosphere. Subsurface tools, including time-lapse 3D seismic, electromagnetic resistivity, and vertical seismic profiling, are used to examine CO_2 plume movement, pressure changes, and the durability of storage sites in the long term. Advanced data integration software enhances the accuracy of these monitoring efforts. Proper monitoring during the injection and post-injection phases enables early leak detection, validation of simulation models, and mass balance verification to ensure stored CO_2 remains contained and in compliance with emission quotas [24][47][48]. ***Table 4*** lists the various monitoring strategies and their effectiveness in practical applications.

CCS (carbon capture and storage) is an important technology for tackling climate change but faces risks like CO_2 leakage, induced seismicity, and high costs [49]. Leakage is the primary concern, often due to aquifer over-pressurization, abandoned wells, or faults and fractures in the cap rock [50]. Maintaining well integrity and preventing over-pressurization are critical for ensuring long-term containment. Caprock integrity is vital, with some cap rocks even self-sealing when exposed to CO_2. Transmissive faults could also serve as leakage pathways, though most have low gas flux rates. Induced seismicity, while rare, may occur in faulted regions [28]. The risks of CCS projects are most prominent during the operational phase, gradually decreasing after injection stops, though never reaching zero. Risks can be categorized as global, related to CO_2 containment, or local, affecting health, safety, and the environment. Local risks arise from elevated CO_2 concentrations, chemical interactions in the subsurface, and fluid displacement caused by CO_2 injection. Additionally, the high costs of capturing CO_2, particularly from power plants, pose an economic challenge, but government subsidies could promote wider adoption of CCS [49]. Effective CCS deployment depends on thorough site characterization, risk assessment, continuous monitoring, and strategies to reduce costs. Addressing these challenges will be essential for the long-term success of CCS as a viable solution to climate change.

Table 4: Objective and Effectiveness of Monitoring Techniques

Monitoring techniques	**Objective**	**Effectiveness**	**Reference**
Seismic Surveys	Monitor subsurface CO_2 plume movement and leakage.	Used in **Sleipner Project (Norway)**. Effective for large-scale monitoring of CO_2 migration but limited by resolution in complex geological formations.	[51] [52] [53]
InSAR (Interferometric Synthetic Aperture Radar)	Detect surface deformations indicating leakage or pressure buildup.	Applied in **In Salah Project (Algeria)**. Effective for large-scale surface movements but less sensitive to small-scale or deep leaks.	[54] [55] [56]
Well Logging	Measure subsurface fluid and pressure changes in wells.	Extensively used in all major CO_2 storage projects like **Weyburn (Canada)** and **Cranfield (USA).** Reliable for pressure and fluid composition data but costly and require frequent access to wells.	[57] [58] [59]
Soil Gas Sampling	To detect CO_2 leakage at the surface.	Used in **Otway (Australia)**. Useful for detecting surface leaks but affected by environmental conditions like soil type and weather.	[60] [61] [62]
Wellbore Pressure Monitoring	Monitor pressure changes within the wellbore to track CO_2 injection and potential leakage	Employed in **Cranfield (USA)**. Effective for detecting early signs of CO_2 leakage and pressure build-up but may require multiple monitoring points along the wellbore for full effectiveness.	[63] [64]
Electrical Resistivity Tomography (ERT)	Track CO_2 migration by measuring changes in the electrical resistivity of subsurface materials.	Used in **Ketzin (Germany)**. Provides high-resolution imaging of CO_2 plume movement, but sensitive to environmental conditions and requires extensive data processing.	[65] [66] [67]
Microseismic Monitoring	Detect seismic events and assess reservoir integrity.	Used in **Decatur (USA)**. Effective for monitoring induced seismicity and CO_2 injection-induced fractures but may miss non-seismic leaks.	[68] [69]

4. Field Scale Project Study:

CO_2 sequestration projects are in progress and being planned globally. These efforts have deepened our understanding of CO_2 storage mechanisms and advanced the development of effective monitoring techniques. ***Table 5*** outlines key field-scale projects, detailing reservoir types, modeling approaches, and monitoring methods.

Table 5: Field-scale projects and modelling and monitoring techniques used

Project	**Reservoir Type**	**Modeling/ Simulation Technique**	**Monitoring Technique**	**Refer-ence**
Sleipner-Norway (1996)	Saline Aquifer	Reservoir simulation (Eclipse), Geomechanical modelling	4D seismic, Gravity Monitoring, InSAR	[70] [51] [71]
Weyburn Midale-Canada (2000)	Saline Aquifer	Reservoir simulation (CMG-GEM), Coupled geomechanical modelling	4D seismic, Wellbore monitoring, Soil gas sampling	[72] [73] [74]
In Salah - Algeria (2004)	Saline Aquifer	Coupled reservoir-geomechanical simulation (Eclipse, CMG-GEM)	Satellite InSAR, 4D seismic, Wellbore pressure monitoring	[75] [76] [77]
Ketzin Pilot Project-Germany (2008)	Saline Aquifer	Reservoir flow simulation (TOUGH2), Coupled thermal modelling	Cross-hole seismic, Wellbore logging, Electrical Resistivity Tomography (ERT)	[78] [66] [67]
Frio Test Site-USA (2008)	Saline Aquifer	Flow and transport simulation (TOUGH2), Reactive Transport Modelling	Crosswell seismic imaging, Wellbore fluid sampling, Pressure monitoring	[79] [80] [81]
Otway Project-Australia (2008)	Depleted gas field	Reservoir simulation (Eclipse), Geochemical modeling, Numerical Modelling	Wellhead pressure monitoring, Downhole seismic, and Soil gas surveys	[82] [83] [84]
Cranfield Project-USA (2009)	Depleted oil field	Reservoir simulation, Reactive transport modelling (TOUGHREACT)	Time-lapse seismic, Wellbore CO2 monitoring, Groundwater sampling	[85] [86] [87] [88]
Aquistore Project-Canada (2011)	Saline Aquifer	Geochemical and flow simulation (CMG-GEM)	Microseismic Distributed temperature sensing (DTS), 4D seismic	[89] [90] [91]

5. Geological CO2 Sequestration Potential in Pakistan:

Pakistan faces rising CO_2 emissions, projected to reach 278 Mt by 2035, complicating its fight against climate change. More than US$ 9.6 billion has already been lost to the economy as a result of these emissions, and biodiversity continues to be affected. As a signatory to the Paris Agreement, Pakistan is committed to limiting global warming to below 1.5°C, emphasizing the importance of CO_2 capture and sequestration strategies [92][93].

The Indus Basin, specifically in the Lower Indus and Potwar Basins, holds vast potential for geological CO_2 sequestration due to its favorable geological features, including deep saline aquifers, depleted gas fields, and unmineable coalbeds [94]. Major gas fields like Sui and Qadirpur are projected to have a storage capacity of around 200 Mt CO_2, contributing to a total estimated 1.6 Gt CO_2 storage capacity in the region [95].

Additionally, the Thar Coalfield presents significant opportunities for enhanced coal bed methane recovery, making it an important site for sequestration efforts [96]. The well-aligned proximity of CO_2 emission sources and storage sites is advantageous for the country's climate mitigation goals.

6. Conclusion and Future Recommendations:

Geological CO_2 sequestration emerged as a promising solution to mitigate climate change by securely storing CO_2 in subsurface formations. This method provides a long-term and stable approach, utilizing geological features like depleted reservoirs and saline aquifers. Despite its potential, the success of CO_2 sequestration relies on comprehensive geotechnical evaluations encompassing site selection, injectivity, storage capacity, and containment integrity. While challenges like leakage risks, ground deformation, and induced seismicity exist, advancements in monitoring and risk management systems help ensure safe, effective sequestration.

The future of sequestration depends on further research into alternative formations like basalt and ultramafic rocks, improved monitoring through numerical modeling and machine learning techniques, and economic feasibility, especially in regions with less developed infrastructure. Integrating sequestration with enhanced oil and coal bed methane recovery could increase deployment. Pakistan's Indus Basin and Thar Coalfield show potential in emerging economies, but international collaboration, regulatory frameworks, and government support are essential for global expansion.

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