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The Effect of Carbon Capture and Storage (CCS) on Quartz Rock and Groundwater: The case study of Thailand

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Abstract

Carbon Capture and Storage (CCS) represents a critical technology for mitigating greenhouse gas emissions by capturing carbon dioxide from emission sources and its permanent sequestration in deep geological formations. This investigation examines the geochemical interactions between CO_2-saturated groundwater and quartz formations in the context of CCS implementation in Thailand's Korat basin. Quartz rock specimens were collected from the Korat basin and exposed to synthetic groundwater formulated to match the chemical composition of local groundwater samples. The synthetic solution was saturated with CO_2 to achieve acidic conditions (pH ~5), simulating the environment created during CO_2 injection. Rock-water interactions were monitored over 28 days under atmospheric conditions to assess both aqueous and solid phase transformations. Results revealed substantial geochemical evolution in both phases throughout the experimental period. Aqueous phase analysis indicated progressive increases in pH, total dissolved solids, and conductivity, consistent with dissolution and mineral trapping mechanisms. Moreover, the increasing of alkalinity, water hardness, and heavy metal concentrations (Fe, Mn, Cu, Zn, Pb, As) demonstrated active mineral dissolution and metal mobilization from the quartz matrix. Solid phase characterization confirmed mineral precipitation processes, evidenced by a 0.18% increase in rock mass, development of calcite crystal formations, and enhanced suspended solid content. While conducted over a limited timeframe, this research underscores the complex geochemical processes associated with CCS operations and emphasizes the necessity for comprehensive impact assessment and monitoring protocols in carbon storage project development.

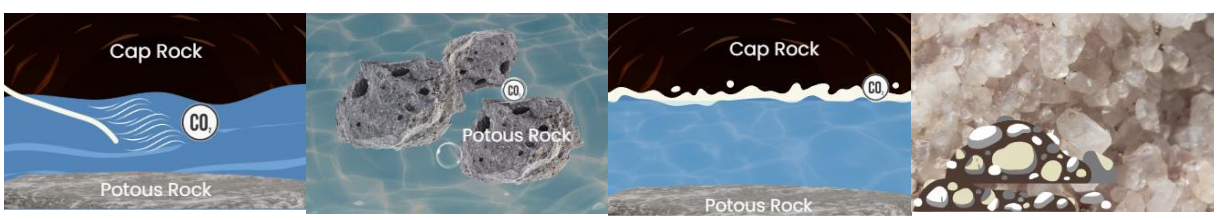
Keywords : Carbon Capture and Storage (CCS); Quartz rock; Groundwater contamination; Mineral trapping

Introduction

The acceleration of industrial development and technological progress has significantly enhanced global living standards while simultaneously contributing to unprecedented levels of atmospheric carbon dioxide (CO_2) emissions, intensifying concerns about climate change and global warming. To address this critical environmental challenge, numerous nations worldwide, including Thailand, have committed to implementing comprehensive greenhouse gas reduction strategies, with Carbon Capture and Storage (CCS) emerging as a pivotal technology in this effort [1].

CCS represents a multi-stage process designed to mitigate CO_2 emissions from major industrial and energy sectors by capturing carbon dioxide at its source and permanently storing it in suitable geological formations. Despite its promising potential for climate change mitigation, CCS implementation raises significant concerns regarding the long-term integrity of storage sites, particularly the risk of CO_2 leakage through fractured rock formations or contamination of groundwater resources. These challenges necessitate comprehensive research and continuous monitoring protocols to ensure the safe and sustainable deployment of CCS technology over extended timeframes [2].

The fundamental mechanisms of CO_2 sequestration in geological formations involve complex interactions between gas, liquid, and solid phases, resulting in four distinct trapping mechanisms that operate over different temporal scales [3], (Figure 1). Structural and stratigraphic trapping serves as the primary containment method, utilizing impermeable cap rock layers to prevent vertical migration of supercritical CO_2 from porous reservoir rocks. Residual trapping occurs through capillary forces that immobilize CO_2 within pore spaces after water displacement. Dissolution trapping involves the formation of carbonic acid through CO_2 dissolution in formation water, creating bicarbonate and carbonate ions that increase fluid density and enhance storage security, particularly under high-salinity and low-temperature conditions. Mineral trapping [4]. represents the most thermodynamically stable sequestration mechanism, involving chemical reactions between dissolved CO_2 and divalent cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) to form stable carbonate minerals including calcite ($CaCO_3$) and magnesium carbonate ($MgCO_3$) [5]. The ability of quartz-rich formations to support the process of CO_2 storage in the form of mineral trapping is crucial for the effectiveness of geological CO_2 sequestration, playing an important role in mitigating climate change [6]. Research has shown that the geochemical interactions in these formations can lead to the formation of stable carbonates, further strengthening their role in CO_2 storage [7]. In the study of the long-term stability of CO_2 storage in quartz rock within synthetic groundwater, along with the potential risk of CO_2 leakage from the storage site, continuous research and monitoring over a period of 2 to 10 years were suggested to ensure the safety and long-term effectiveness of CO_2 sequestration for future sustainability.



a. Structural and stratigraphic trapping b. Residual trapping c. Dissolution trapping d. Mineral trapping

Figure 1 Carbon dioxide capture processes of carbonation interactions

Thailand's Khorat Plateau region contains extensive quartz-rich geological formations that present unique opportunities for CO_2 sequestration research. Quartz formations, primarily composed of silicon dioxide, frequently contain associated minerals such as feldspar that provide essential calcium and magnesium content necessary for mineral trapping processes [3]. The porous microstructure of these quartz rocks potentially enhances their CO_2 storage capacity through increased surface area for geochemical reactions and improved permeability for fluid flow. The formation of dissolution-resistant carbonate minerals through CO_2-water-rock interactions represents a critical pathway for long-term carbon sequestration, with research demonstrating the potential for stable carbonate formation in quartz-rich environments [6, 7].

However, the geochemical processes associated with CO_2 injection create significant environmental considerations that require careful evaluation [8, 9]. The dissolution of CO_2 in groundwater produces carbonic acid [10], lowering pH and promoting enhanced mineral dissolution and ion mobilization. Previous studies have documented the release of various cations including Ca^{2+}, Mg^{2+}, and potentially toxic heavy metals such as Pb^{2+}, As^{2+}, and Zn^{2+} from host rock formations following CO_2 exposure [11]. These geochemical alterations can substantially impact groundwater quality through changes in taste, odor, color, and overall potability [12], while also affecting key water chemistry parameters including Total Dissolved Solids (TDS), bicarbonate (HCO^{3-}), and sulfite (SO_3^{2-}) concentrations. Although Oxidation Reduction Potential (ORP) typically remains stable during these processes [13], the cumulative effects on groundwater systems highlight the critical importance of comprehensive impact assessment and monitoring strategies.

Given the absence of previous research examining quartz rock formations for CO_2 sequestration applications in Thailand, this study addresses a significant knowledge gap in understanding the geochemical behavior of Thailand's geological formations under CCS conditions. The research aims to evaluate the CO_2 storage potential of quartz rocks from the Khorat Plateau while simultaneously assessing the associated impacts on groundwater chemistry and heavy metal mobilization. Through systematic investigation of physical and chemical changes in both rock and water phases following CO_2 exposure, this study seeks to provide essential data for evaluating the feasibility and environmental implications of implementing CCS technology using Thailand's indigenous geological resources. The findings will contribute to the broader understanding of CO_2-water-rock interactions in tropical geological settings and support evidence-based decision-making for future CCS deployment in Southeast Asia.

Materials and Methods

Synthetic groundwater

Synthetic water was prepared using the references data of the groundwater sampling from the well number of 5705D015 in Korat basin, Mueang Nakhon Ratchasima, Nakhon Ratchasima, Thailand. The synthetic water contained 19 mg/L of magnesium ion (Mg^{2+}) and 39 mg/L of calcium ion (Ca^{2+}). The reference data of the heavy metal concentration on this groundwater are less than the Thailand groundwater quality standard and provided in the Table 1.

Synthetic groundwater was prepared to replicate the chemical composition of local groundwater samples. To simulate the acidic conditions resulting from CO_2 injection, the solution was saturated with carbon dioxide, achieving a pH of approximately 5. Quartz rock samples were then immersed in the CO_2 saturated synthetic groundwater. The experiments were conducted under atmospheric conditions, and changes in the quartz were monitored over a 28-day period. The temperature, total dissolved solid (TDS), pH, and conductivity were measure daily using the Multi-parameter PCS Tester 35#ECPCSTEST35. The suspended solid (SS), alkalinity (Alk), hardness, and heavy metals were analyzed before (day 0) and after the period (day 28).

Table 1 Table of heavy metal concentrations in the Khorat Basin and groundwater quality standards [14–16]

Parameters	Sampling	Thailand standards (2009)	WHO standards (2004)	EPA standards (2018)
Ca^{2+}	39	-	-	-
Mg^{2+}	19	-	-	-
Fe (mg/L)	0.1	< 0.5	-	< 0.3
Mn (mg/L)	nd	< 0.3	< 0.4	< 0.05
Cu (mg/L)	nd	< 1	< 2.0	< 1.3
Zn (mg/L)	1.6	< 5	-	< 5
Pb (mg/L)	0.001	< 0.05	< 0.01	< 0.015
Cr (mg/L)	< 0.0024	-	-	-
As (mg/L)	< 0.0028	<0.05	<0.01	<0.01

Quartz rock

Quartz rock samples were collected from the Korat Basin, located in Mueang Nakhon Ratchasima, Nakhon Ratchasima Province, Thailand. A porous quartz sample was selected and cut into rough cubic pieces measuring approximately 30 × 33 × 48 mm to facilitate observation of changes during the experiment. The chemical and physical properties of the quartz were analyzed both before and after the 28-day immersion in CO_2-saturated synthetic groundwater. Two key parameters were measured: (1) the total mass of the rock, and (2) its mineral composition, determined using X-ray diffraction (XRD).

Results and Discussion

The results of the effect of carbon capture and storage (CCS) on quartz rock and groundwater in this study can be categorized into the effect to 1) pore fluid phase occurring in the synthetic groundwater with saturated CO_2 dissolution and 2) solid phase occurring in quartz rock. Testing parameters, methods and the results for liquid phase and solid phase were present in Table 2.

Pore fluid phase

After 28 days of soaking quartz rock samples in synthetic groundwater saturated with dissolved carbon dioxide gas, the distinguish changes in liquid were observed. Figure 2 showed the changes in water physical and chemical properties in the liquid phase during the samplings period. The temperature was almost steady at 26.7±0.61°C confirmed that observed changes are due to chemical processes, not thermal effects.

After injecting CO_2 gas into the synthetic groundwater (Day 0), CO_2 was transferred in the water and formed the liquid form dissolved CO_2. This hydrolysis process of CO_2 formed carbonic acid (H_2CO_3) which caused the pH drop to about 5, as shown in the following equations:

$$CO_2(g) \leftrightharpoons CO_2\,(aq) \qquad \textbf{Equation 1}$$

$$CO_2\,(aq) + H_2O(l) \leftrightharpoons H_2CO_3^-(aq) \qquad \textbf{Equation 2}$$

The decrease in pH is also associated with a decrease in oxidation-reduction potential (ORP), reflecting the increased reducing environment caused by CO_2 dissolution. Low pH and ORP enhance mineral weathering and metal leaching from rocks.

Then, there was a rapid increase in the pH, conductivity, and TDS in the first five days due to the reaction between the carbonate and hardness (Ca^{2+} and Mg^{2+}) and bicarbonate (HCO_3^-) of the synthetic groundwater. This process caused mineral trapping that the dissolution was transformed into other minerals by chemical precipitation process, as represented by the following equations:

$$Ca^{2+}, Mg^{2+} + CO_3^{2-}\,(aq) \rightarrow CaCO_3\,(s), MgCO_3\,(s) \qquad \textbf{Equation 3}$$

Table 2 Result of testing parameters and methods for synthetic groundwater with saturated CO_2 dissolution and quartz rock

Testing	Day 0	Day 28	Test method
Pore fluid phase			
pH	5.25	8.49	Multi-parameter PCS Tester 35#ECPCSTEST35
Conductivity (µS/cm)	90.5	176.7	
TDS (mg/L)	64.1	125.0	
Alk (mg/L)	6.60	28.00	Titration method
Hardness (mg/L)	66.80	80.00	
TOC	-1.543	-13.080	Combustion catalytic oxidation method
Fe (mg/L)	nd	<0.05	Atomic Absorption Spectrometry
Mn (mg/L)	nd	<0.04	
Cu (mg/L)	nd	<0.03	
Zn (mg/L)	<0.04	0.10	
Pb (mg/L)	nd	<0.05	
Cr (mg/L)	nd	nd	
As (mg/L)	<0.002	<0.002	
Solid phase			
SS (mg/L)	0.5	6.0	Gravimetric method
Mass (g)	70.6854	70.8098	Gravimetric method
Quartz (%)	98.2	97.3	XRD, BrukerD8 Advance diffractometer, ICDD method
Calcite (%)	1.8	2.7	

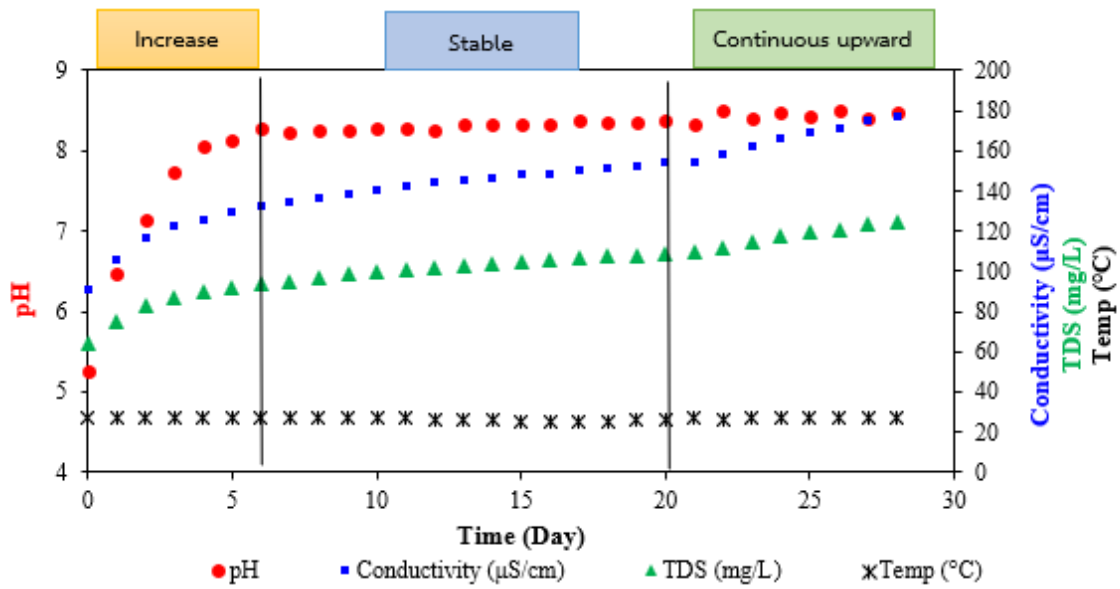


Figure 2 Temperature**,** pH, TDS, and conductivity of water sample over 28 days period

After that the pH was relatively stable after day at around 8-8.5 for the rest of the period, indicating a buffering reaction or the dissolution of alkaline minerals. Meanwhile, increases in conductivity, TDS, SS, alkalinity, hardness, and heavy metals (Fe, Mn, Cu, Zn, Pb, As) were observed due to the acidic properties of CO_2 dissolved in water. This led to the leaching of minerals and heavy metals from the quartz rock samples. However, the elevated values remained below the groundwater quality standards as shown in Table 1 [14]. The reactions mentioned above are expressed as follows.

$$H^+ + \text{Quartz rock} \rightarrow Ca^{2+}, Mg^{2+} + \text{heavy metal} \quad \textbf{Equation 4}$$

The overall, pH increased from acidic (~5.5) to alkaline (~8.5) due to neutralization of CO_2 acidified water by quartz or other minerals and conductivity and TDS trends reflect ongoing ion release into the solution. However, the experiment duration of 28 days is too short for the stabilization phase of the reaction between quartz rock and CO_2 dissolution. To observe clearer and stable results, a testing period of 2-10 years is required to allow the reactions occurring in the CO_2 dissolution process and mineral precipitation to fully take place, enabling effective carbon sequestration through mineral trapping [17].

Solid phase

The significant physical changes were observed indicating mineral trapping process. The dry mass increased by 0.18%, and the calcite structure within crystal morphology showed enhancement in the XRD (0.9%). This change indicated physical alterations resulting from the reaction between the rock and the water, leading to the formation and mineral precipitation of calcite. These changes suggested that CO_2 injection influenced both the pore fluid and the solid phase of the rock. During mineralization, divalent metal ions (M^{2+}) bond with carbonate ions, resulting in precipitation and the formation of stable calcite ($CaCO_3$) minerals [18] inside quartz rock structure.

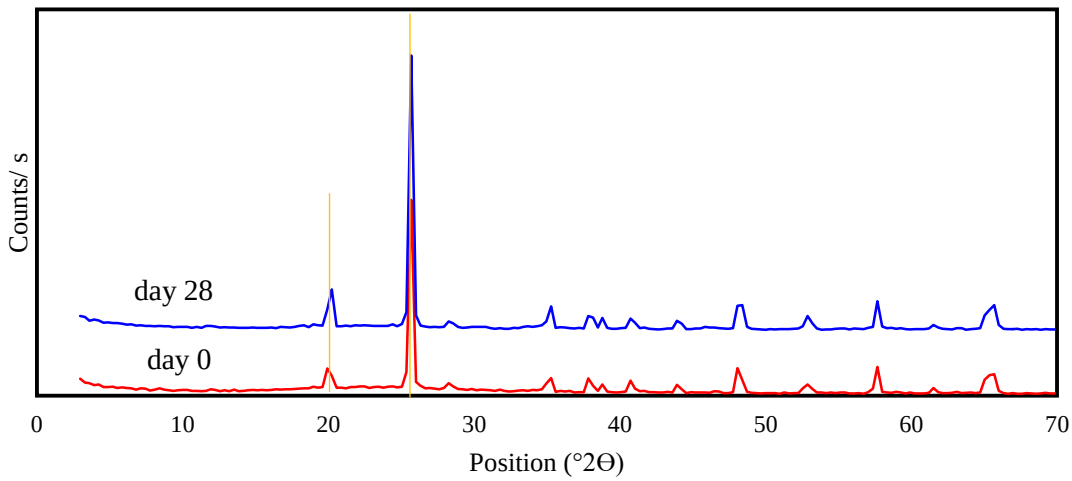


Figure 3 X-ray diffraction (XRD) of quartz rock at day 0 and day 28

Moreover, Figure 4 represented the occurrent of the small white precipitate in the sediments and beneath or around the edges of the rock and the increase of SS from 0.5 mg/l to 6 mg/l confirmed the mineral trapping process of divalent metal ions (M^{2+}) bond with carbonate ions as presented in Equation 3. The minerals in quartz rock are abundant, and when a reaction occurs, it leads to the leaching of these minerals. This process results in the formation of heavy metals in a dissolved form in the water, which then precipitate and form solid compounds [17].

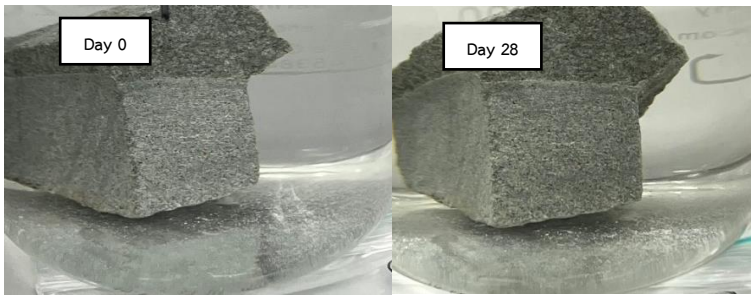


Figure 4 An experiment of soaking quartz rock in synthetic groundwater for a period of day 0 and day 28

Conclusions

This investigation of CO_2-water-rock interactions using quartz formations from Thailand's Korat basin provides valuable insights into the geochemical processes associated with carbon capture and storage implementation in tropical geological settings. The experimental findings demonstrate that quartz rock formations exhibit significant potential for CO_2 sequestration through multiple trapping mechanisms, while simultaneously revealing important environmental considerations that must be addressed in CCS project development.

Future research should focus on extending the experimental timeframe to better understand long-term geochemical evolution, investigating mitigation strategies for heavy metal mobilization, and conducting field-scale studies to validate laboratory findings under realistic geological conditions. This study represents a critical first step in evaluating CCS potential in Thailand and provides a foundation for evidence-based decision-making regarding the implementation of carbon sequestration technologies as part of the nation's climate change mitigation strategy. The findings emphasize that while geological CO_2 storage shows promise, successful implementation requires careful consideration of both storage efficiency and environmental protection to ensure sustainable and responsible deployment of CCS technology.

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