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Pore-Scale Modeling of Co_2-Brine-Rock Interactions in Carbonate Reservoirs: Numerical and Experimental Evaluation of Geochemical and Geomechanical Changes Occurring During Co_2 Injection in Carbonate Formations

Julius Olatunde Omisola [1*], **Emmanuel Augustine Etukudoh** [2], **Odira Kingsley Okenwa** [3], **Gilbert Isaac Tokunbo Olugbemi** [4], **Elemele Ogu** [5]
[1] Platform Petroleum Limited, Nigeria
[2] Independent Researcher, Nigeria
[3] Independent Researcher, Benin City, Nigeria
[4] Chevron Nigeria limited, Nigeria
[5] Independent Researcher, Nigeria

* Corresponding Author: **Julius Olatunde Omisola**

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Abstract

The injection of CO_2 into carbonate reservoirs for long-term sequestration induces complex geochemical and geomechanical interactions at the pore scale, influencing storage capacity and reservoir integrity. This study presents a combined numerical and experimental approach to evaluating these interactions, focusing on mineral dissolution, precipitation, and their impact on permeability and mechanical stability. Laboratory-scale experiments using high-pressure flow cells and microfluidic devices simulate CO_2-brine-rock interactions under reservoir conditions. Advanced imaging techniques, including X-ray micro-computed tomography (μCT) and scanning electron microscopy (SEM), provide insights into pore-scale alterations and reaction dynamics. Complementing the experimental analysis, a numerical model incorporating reactive transport equations and geomechanical coupling is developed to predict dissolution patterns, permeability evolution, and rock strength variations. The Lattice Boltzmann Method (LBM) and Finite Volume Method (FVM) are employed to simulate multiphase flow and mineralogical changes over time. Model calibration with experimental data ensures accuracy in representing key processes such as acid-induced pore enlargement, precipitation of secondary minerals, and stress redistribution in the rock matrix. Results reveal that CO_2 injection leads to significant heterogeneities in pore structure, enhancing permeability in some regions while inducing mechanical weakening in others. These highlight the dual impact of CO_2 sequestration in carbonate formations: improved injectivity but potential risks to reservoir stability. Understanding these dynamics is crucial for optimizing storage strategies and mitigating leakage risks. This contributes to advancing predictive models for subsurface CO_2 sequestration, supporting the safe and efficient implementation of carbon capture and storage (CCS) technologies. Future research should refine upscaling methodologies and incorporate real-time monitoring techniques for improved assessment of CO_2 behavior in geological formations.

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1. Introduction

The increasing concentration of atmospheric carbon dioxide (CO_2) due to fossil fuel combustion and industrial activities has led to severe environmental concerns, including global warming and ocean acidification (Basiru *et al.*, 2023; Johnson *et al.*, 2024). Carbon capture and storage (CCS) has emerged as a viable strategy to mitigate these effects by injecting CO_2 into deep geological formations, including depleted oil and gas reservoirs, saline aquifers, and carbonate formations. Among these, carbonate reservoirs are particularly attractive for CO_2 sequestration due to their extensive global distribution and high porosity, which provide significant storage capacity (Digitemie and Ekemezie, 2024). However, the injection of CO_2 into these reservoirs induces complex geochemical and geomechanical interactions that can affect the integrity of the storage site.

When CO_2 is injected into a carbonate reservoir, it dissolves in the resident brine, forming carbonic acid. This acid lowers the pH of the formation water, leading to the dissolution of carbonate minerals such as calcite and dolomite (Weldegeorgis *et al.*, 2024). While this dissolution can enhance permeability and CO_2 injectivity, it may also create preferential flow paths, increasing the risk of leakage. Furthermore, the precipitation of secondary minerals, such as calcium sulfate and iron carbonates, can alter pore structures and reduce permeability in certain areas. In addition to these geochemical effects, geomechanical changes such as stress redistribution, rock weakening, and potential fracturing pose challenges to long-term storage stability. Therefore, understanding the coupled geochemical and geomechanical processes at the pore scale is crucial for optimizing CO_2 sequestration strategies and ensuring reservoir integrity.

This review aims to provide a comprehensive assessment of the geochemical and geomechanical changes that occur at the pore scale during CO_2 injection into carbonate formations. The specific objectives include. The review focuses on the dissolution and precipitation of minerals induced by CO_2 injection, as well as the subsequent effects on porosity, permeability, and rock mechanical properties. By analyzing these interactions at the pore scale, a deeper understanding of how microscale changes influence the overall behavior of the reservoir is achieved. This integrates experimental investigations and numerical modeling approaches to simulate and analyze CO_2-brine-rock interactions. Experimental methods, such as high-resolution imaging and microfluidics, provide empirical evidence of reaction dynamics, while numerical models offer predictive capabilities for long-term CO_2 sequestration performance (Onukwulu *et al.*, 2021). By addressing these objectives, the review contributes to improving the predictability and safety of CO_2 storage in carbonate reservoirs, aiding in the development of more efficient CCS strategies.

The review is structured to provide a systematic exploration of the experimental and numerical approaches used to study pore-scale CO_2-brine-rock interactions. Experimental approaches, this section details laboratory techniques used to investigate CO_2-induced geochemical and geomechanical changes in carbonate reservoirs (Daramola *et al.*, 2023). High-pressure flow cells, microfluidic devices, and imaging techniques such as X-ray micro-computed tomography (μCT) and scanning electron microscopy (SEM) are discussed. These methods enable direct observation of pore-scale alterations and provide valuable data for model validation. The next section presents computational modeling techniques used to simulate multiphase flow, reactive transport, and geomechanical effects in carbonate reservoirs (Onita *et al.*, 2023). Key modeling approaches, including the Lattice Boltzmann Method (LBM) and Finite Volume Method (FVM), are explored, highlighting their role in predicting dissolution patterns, permeability evolution, and rock deformation. The review then synthesizes the findings from experimental and numerical studies, discussing the implications for CO_2 storage efficiency and reservoir stability. The potential risks associated with pore-scale heterogeneities, permeability enhancement, and mechanical weakening are analyzed (Farooq e al., 2024). The final section summarizes the key insights from the review and suggests future research directions, including advancements in real-time monitoring, improved upscaling techniques, and integration of machine learning for predictive modeling. By combining experimental observations with numerical simulations, this review enhances the understanding of CO_2-induced geochemical and geomechanical changes in carbonate reservoirs, providing a foundation for optimizing long-term CCS strategies.

2. Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was adopted to systematically review and analyze literature on pore-scale modeling of CO_2-brine-rock interactions in carbonate reservoirs. This approach ensures a transparent, comprehensive, and reproducible evaluation of relevant studies that address numerical and experimental investigations into geochemical and geomechanical changes occurring during CO_2 injection.

A structured search strategy was implemented using multiple academic databases, including Scopus, Web of Science, and Google Scholar, to identify peer-reviewed articles, conference papers, and technical reports published between 2000 and 2024. Keywords and Boolean operators were applied to refine search results, using terms such as "CO_2-brine-rock interactions," "carbonate reservoirs," "pore-scale modeling," "geochemical reactions," "geomechanical changes," "numerical simulation," and "experimental evaluation." Additional literature was retrieved through cross-referencing relevant studies cited in selected papers.

The eligibility criteria for study selection included research focused on pore-scale numerical modeling or experimental studies evaluating geochemical and geomechanical processes in carbonate formations during CO_2 injection. Studies that primarily addressed sandstone reservoirs, large-scale field studies without pore-scale analysis, or those lacking quantitative geochemical or geomechanical assessments were excluded. The initial database search yielded 1,240 records, which were screened based on titles and abstracts, resulting in 375 full-text articles assessed for eligibility. After applying inclusion and exclusion criteria, 112 studies were selected for qualitative and quantitative synthesis.

Data extraction was conducted systematically, capturing key variables such as study objectives, experimental methods, numerical modeling techniques, reaction kinetics, changes in porosity and permeability, mineral dissolution and precipitation mechanisms, and mechanical stability assessments (Johnson *et al.*, 2024; Egbumokei *et al.*, 2024). The extracted data were synthesized to identify common trends, knowledge gaps, and methodological limitations in the existing literature. Risk of bias was assessed using established quality appraisal tools to ensure the reliability of findings.

The PRISMA approach provided a rigorous and structured framework for evaluating the current state of knowledge on pore-scale modeling of CO_2-brine-rock interactions in carbonate reservoirs. The systematic review highlights the complexities of coupled geochemical and geomechanical processes during CO_2 injection and underscores the need for integrated experimental and numerical frameworks to enhance predictive accuracy in carbonate reservoir management.

2.1. Fundamentals of CO_2-brine-rock interactions in carbonate reservoirs

Carbonate reservoirs are among the most significant geological formations for hydrocarbon production and CO_2 sequestration, accounting for nearly 60% of the world's oil and gas reserves. These reservoirs are primarily composed of calcium carbonate ($CaCO_3$) minerals, such as calcite, dolomite, and aragonite, which exhibit high porosity and permeability due to natural dissolution processes and extensive fracturing (Johnson *et al.*, 2024). The heterogeneous nature of carbonate reservoirs, resulting from diagenetic alterations, makes them complex but highly attractive for CO_2 storage.

The significance of carbonate reservoirs in CO_2 sequestration stems from their ability to trap injected CO_2 through multiple mechanisms, including structural trapping, residual trapping, solubility trapping, and mineral trapping. Structural trapping relies on impermeable caprocks to prevent CO_2 migration, while residual trapping immobilizes CO_2 in pore spaces through capillary forces. Solubility trapping occurs when CO_2 dissolves in brine, forming carbonic acid, which interacts with carbonate minerals. Mineral trapping is the most stable form of sequestration, where CO_2 reacts with reservoir minerals to form solid carbonates, ensuring long-term storage security (Ekemezie and Digitemie, 2024). However, the injection of CO_2 triggers a series of complex geochemical and geomechanical reactions that can significantly alter reservoir properties, necessitating a comprehensive understanding of these interactions.

Upon injection into a carbonate reservoir, CO_2 comes into contact with formation brine, leading to its dissolution and the formation of carbonic acid (H_2CO_3) according to the reaction:

$CO2+H2O \rightleftharpoons H_2CO_3$

This reaction lowers the pH of the brine, enhancing the acidity of the formation water. The increased acidity accelerates the dissolution of carbonate minerals, altering the porosity and permeability of the reservoir (Onukwulu *et al.*, 2021). The extent of CO_2 dissolution in brine depends on reservoir conditions such as pressure, temperature, salinity, and the initial mineral composition.

Carbonic acid formed during CO_2 dissolution reacts with carbonate minerals, leading to their dissolution:

- **Calcite ($CaCO_3$):**

$CaCO3+H2CO3 \rightarrow Ca2++2HCO3-$

- **Dolomite ($CaMg(CO_3)_2$):**

$CaMg(CO3)2+2H2CO3 \rightarrow Ca2++Mg2++4HCO3-$

- **Aragonite ($CaCO_3$, polymorph of calcite):**

Aragonite undergoes a dissolution process similar to calcite, but its higher solubility can lead to faster structural alterations in carbonate formations.

Mineral dissolution increases porosity and permeability, potentially enhancing CO_2 injectivity. However, excessive dissolution can destabilize the reservoir structure, creating preferential flow paths that could compromise caprock integrity and increase leakage risks (Onukwulu *et al.*, 2022). In addition to mineral dissolution, CO_2 injection can lead to the precipitation of secondary minerals such as calcium sulfate ($CaSO_4$), iron carbonate ($FeCO_3$), and silica-based precipitates. These reactions occur due to the release of ions from dissolving minerals and subsequent re-equilibration of the geochemical system. The precipitation of these secondary minerals can reduce pore throat diameters, decreasing permeability and potentially clogging flow pathways. This process can counteract the porosity increase from dissolution, leading to heterogeneous reservoir alterations.

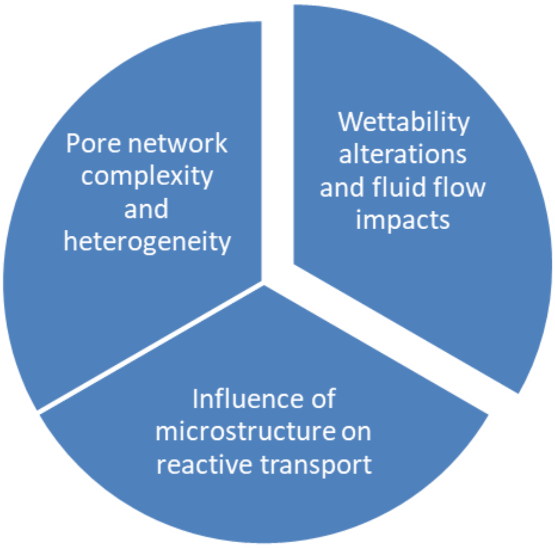

Fig 1: Pore-scale characteristics of carbonate reservoirs

The combined effects of mineral dissolution and precipitation result in significant changes to the porosity and permeability of the carbonate reservoir. As carbonate minerals dissolve, pore spaces enlarge, increasing overall porosity and improving fluid flow. However, mineral precipitation can locally reduce permeability, creating zones of flow restriction. These heterogeneous changes can lead to differential compaction and localized stress variations, potentially affecting reservoir performance (Fredson *et al.*, 2021). The dissolution of carbonate minerals weakens the rock matrix, reducing mechanical strength and increasing the risk of subsurface deformation. In cases where dissolution is uneven, stress redistribution can occur, leading to rock fracturing or subsidence. The formation of fractures and faults can create preferential leakage pathways, jeopardizing the long-term security of CO_2 storage (Egbumokei *et al.*, 2024). Additionally, the reduction in rock strength can lead to caprock failure, increasing the likelihood of CO_2 migration into overlying formations. The precipitation of secondary minerals, while potentially reducing permeability, can also enhance mechanical strength by cementing grains together. However, this effect is highly dependent on the spatial distribution and composition of the precipitated minerals. In some cases, mineral precipitation can lead to stress accumulation, inducing microfracturing and further altering the reservoir's geomechanical stability. Understanding the fundamental interactions between CO_2, brine, and carbonate rocks at the pore scale is crucial for optimizing CO_2 sequestration strategies. The dissolution of carbonate minerals enhances porosity and permeability but can also weaken reservoir integrity, while secondary mineral precipitation can reduce permeability and potentially stabilize the rock matrix (Onukwulu *et al.*, 2021; Johnson *et al.*, 2024). These coupled geochemical and geomechanical effects must be carefully evaluated to ensure the efficiency and safety of CO_2 storage in carbonate reservoirs. Future research should focus on integrating experimental observations with numerical models to predict long-term reservoir behavior and mitigate potential risks (Onukwulu *et al*., 2024; Egbumokei *et al*., 2024).

2.2. Experimental investigation of CO_2-brine-rock interactions

The experimental investigation of CO_2-brine-rock interactions in carbonate reservoirs is essential for understanding the geochemical and geomechanical changes that occur during CO_2 injection (Basiru *et al*., 2023; Onukwulu *et al*., 2024). Laboratory-based studies provide direct insights into mineral dissolution, porosity alterations, and permeability variations at the pore scale. Advanced experimental techniques are employed to replicate reservoir conditions and quantify reaction mechanisms, enabling the validation of numerical models.

To examine CO_2-brine-rock interactions, high-pressure flow cells and microfluidic devices are commonly used to simulate in-situ reservoir conditions (Egbumokei *et al*., 2024). High-pressure flow cells allow controlled CO_2 injection into carbonate samples, maintaining temperature, pressure, and flow rates similar to those encountered in subsurface environments (Johnson *et al*., 2024). These setups facilitate real-time monitoring of dissolution and precipitation processes under dynamic conditions. Microfluidic devices, on the other hand, provide a two-dimensional representation of the pore structure, enabling visualization of fluid-rock interactions at the microscale. They are particularly useful for tracking real-time changes in mineral phases and flow pathways. A range of imaging techniques is employed to analyze geochemical and structural changes within carbonate samples. X-ray computed tomography (X-ray CT) provides non-destructive, three-dimensional visualization of pore structures and their evolution over time. It enables quantitative assessment of porosity and permeability alterations. Scanning electron microscopy (SEM) offers high-resolution imaging of mineral surfaces, revealing dissolution patterns and secondary mineral formations. Raman spectroscopy is utilized to identify mineral composition and detect chemical changes in reaction products, providing molecular-level insights into carbonate dissolution and precipitation dynamics (Basiru *et al*., 2023).

Before conducting CO_2 injection experiments, carbonate samples are thoroughly characterized to establish baseline properties. Mineral composition analysis is performed using techniques such as X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDS) to determine the presence of key minerals, including calcite, dolomite, and aragonite. The heterogeneity in mineral distribution influences reaction kinetics and porosity evolution during CO_2 injection. Initial porosity and permeability assessments are conducted using mercury intrusion porosimetry (MIP) and gas or liquid permeability measurements (Onukwulu *et al*., 2023). These assessments provide essential data on fluid flow characteristics and potential reaction sites within the carbonate matrix. Understanding the initial state of the reservoir rock is crucial for interpreting experimental results and evaluating the extent of geochemical alterations induced by CO_2 injection (Ekemezie and Digitemie, 2024).

CO_2 injection experiments are performed under controlled laboratory conditions to investigate reaction kinetics and their dependence on environmental parameters (Fredson *et al*., 2022). The dissolution of carbonate minerals is strongly influenced by pH and temperature conditions. Acidification occurs as CO_2 dissolves in brine, forming carbonic acid, which enhances mineral dissolution. Experiments are designed to observe how varying pH levels affect reaction rates and mineral stability. Temperature variations are also explored, as higher temperatures generally accelerate reaction kinetics, impacting dissolution and precipitation processes. Flow rate and pressure variations play a critical role in controlling geochemical reactions and transport mechanisms (Digitemie and Ekemezie, 2024). Experiments investigate the impact of different flow velocities on mineral dissolution, as higher flow rates can enhance mass transfer but may also limit reaction time at mineral surfaces. Similarly, pressure variations influence CO_2 solubility in brine, altering the extent of acidification and subsequent mineral dissolution. High-pressure experiments simulate deep reservoir conditions, providing insights into the geochemical behavior of carbonate formations under realistic CO_2 storage scenarios (Basiru *et al*., 2022).

The experimental results are analyzed to determine the spatial and temporal evolution of pore-scale dissolution patterns. X-ray CT and SEM images reveal how carbonate dissolution progresses, leading to increased porosity and altered permeability. In some cases, localized dissolution can create preferential flow pathways, enhancing CO_2 migration. However, heterogeneous dissolution patterns may also lead to pore collapse, reducing permeability and affecting reservoir integrity (Onukwulu *et al*., 2022). Reaction-induced heterogeneities arise from the interplay between mineral dissolution and secondary mineral precipitation. While calcite and dolomite dissolution increase porosity, the precipitation of secondary minerals, such as gypsum or silica, can clog pore spaces, altering flow dynamics. These heterogeneities impact long-term CO_2 storage efficiency and mechanical stability, necessitating further investigation into coupled geochemical and geomechanical effects. Overall, experimental investigations provide valuable data on pore-scale processes governing CO_2-brine-rock interactions (Egbumokei *et al*., 2024). The findings contribute to refining numerical models, improving predictions of carbonate reservoir behavior during CO_2 sequestration, and guiding the development of effective carbon storage strategies.

2.3. Numerical modeling of pore-scale CO_2-brine-rock interactions

Numerical modeling is essential for understanding and predicting the complex geochemical and geomechanical interactions occurring at the pore scale during CO_2 injection into carbonate reservoirs (Ekemezie and Digitemie, 2024). By simulating reactive transport and mineral dissolution-precipitation dynamics, numerical models help in optimizing carbon storage strategies and mitigating potential risks associated with reservoir integrity. Various computational approaches are used to capture the coupled processes governing CO_2-brine-rock interactions, ensuring accurate predictions of pore-scale changes (Iriogbe *et al*., 2024).

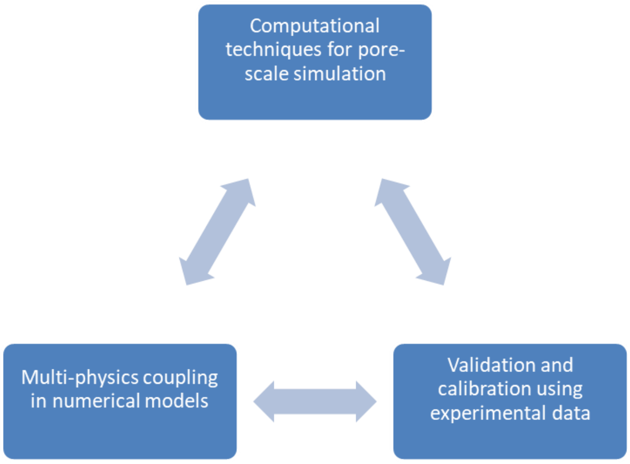

Fig 2: Numerical modeling of co_2-brine-rock interactions

Numerical models of CO_2-brine-rock interactions rely on a set of governing equations describing fluid flow, reactive transport, and mechanical deformation. The reactive transport equations account for mass transport through advection, diffusion, and dispersion, while incorporating chemical reactions that drive mineral dissolution and precipitation.

The coupling of geochemical and geomechanical models is crucial for capturing the feedback mechanisms between mineral dissolution, porosity evolution, and mechanical stability (Uchendu *et al*., 2024). Geomechanical models use equations of elasticity and plasticity to assess stress-strain behavior and predict deformation due to changes in porosity and permeability. Several computational approaches are employed to simulate CO_2-brine-rock interactions at the pore scale, each offering distinct advantages in capturing reactive transport and mechanical effects (Johnson *et al*., 2024). The Lattice boltzmann method (LBM) is a mesoscopic approach that models fluid flow and transport processes using discrete particle dynamics. LBM is particularly effective for simulating complex porous media due to its ability to handle irregular geometries and multi-phase flow interactions. It solves the Boltzmann transport equation and is widely used for modeling mineral dissolution and precipitation in carbonate formations (Onukwulu *et al*., 2024). The Finite volume method (FVM**)** is another popular technique for solving transport equations in porous media. FVM discretizes the governing equations into control volumes, ensuring mass conservation at each grid cell. It is commonly used in computational fluid dynamics (CFD) simulations to model reactive transport in porous networks. The method provides high accuracy in capturing concentration gradients and reaction fronts. Phase-field modeling is employed to represent mineral dissolution and precipitation with high spatial resolution. This method tracks solid-fluid interfaces through a continuous field variable, allowing seamless simulation of evolving mineral structures. Phase-field models are particularly useful for studying heterogeneous dissolution patterns and precipitation-induced permeability alterations.

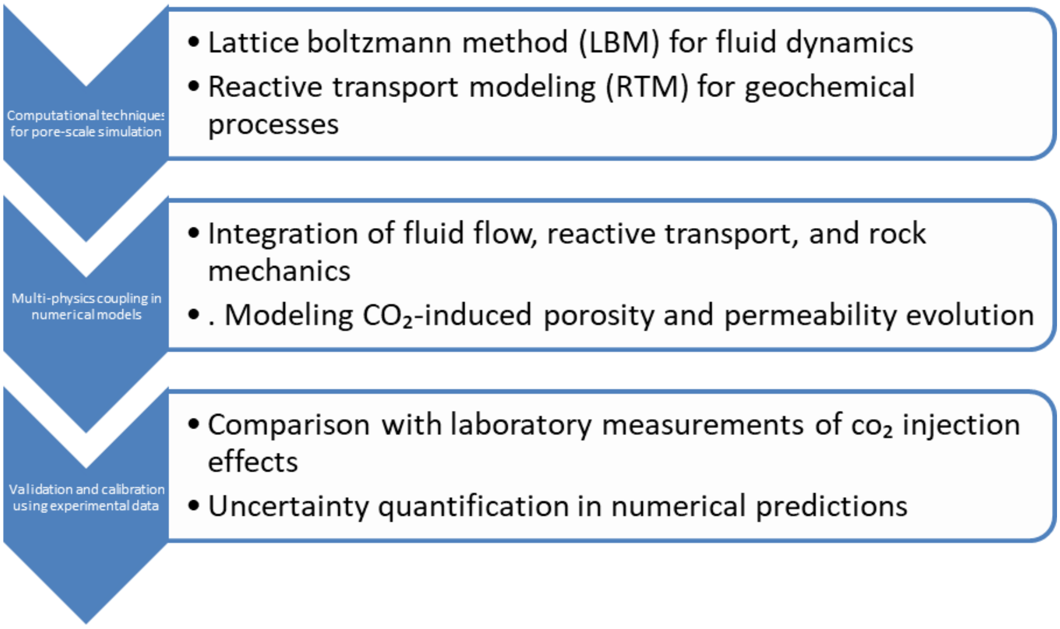

Fig 3: Subdivisions of numerical modeling of co_2-brine-rock interactions

To ensure the accuracy and reliability of numerical simulations, model calibration and validation are performed using experimental data. Comparison with high-resolution experimental datasets, including X-ray CT and SEM images, allows for the refinement of reaction kinetics and transport parameters. Calibration involves adjusting reaction rate constants, diffusion coefficients, and mineral solubilities to match observed pore-scale dissolution patterns. Sensitivity analysis is conducted to assess the impact of key parameters, such as CO_2 solubility, flow rate, and mineral composition, on simulation results. By systematically varying these parameters, the robustness of the model can be evaluated, and uncertainties can be quantified. Sensitivity studies help identify critical factors influencing CO_2-brine-rock interactions, guiding further improvements in numerical modeling frameworks (Digitemie and Ekemezie, 2024). Overall, numerical modeling provides a powerful tool for investigating the pore-scale dynamics of CO_2 injection into carbonate reservoirs. By integrating reactive transport equations, advanced computational techniques, and experimental validation, these models enhance our understanding of geochemical and geomechanical changes, ultimately contributing to more effective and secure carbon sequestration strategies.

2.4. Discussion and interpretation of results

Understanding the results of experimental and numerical investigations of CO_2-brine-rock interactions in carbonate reservoirs is critical for assessing the feasibility of CO_2 sequestration and its potential long-term impacts (Onukwulu *et al*., 2022; Onita *et al*., 2023). This discusses key findings related to geochemical evolution, changes in pore structure and permeability, and their implications for reservoir stability and CO_2 storage efficiency.

The interaction between injected CO_2, brine, and carbonate minerals initiates a series of geochemical reactions that significantly alter the reservoir's chemical composition. When CO_2 dissolves in brine, it forms carbonic acid, which lowers the pH of the solution. This acidification enhances the dissolution of carbonate minerals such as calcite, dolomite, and aragonite. Additionally, secondary mineral precipitation occurs as a result of changes in the local chemical environment. Minerals such as gypsum, anhydrite, and silica-based precipitates may form in areas of high ion concentration, leading to localized reductions in porosity (Onukwulu *et al*., 2021). Experimental observations confirm that mineral precipitation often occurs near dissolution fronts, creating heterogeneities in the rock matrix.

Pore-scale imaging techniques, including X-ray computed tomography (X-ray CT) and scanning electron microscopy (SEM), reveal significant alterations in pore structure due to mineral dissolution and precipitation. These changes have a direct impact on the permeability of carbonate formations, influencing fluid flow behavior and CO_2 migration pathways. The dissolution of carbonate minerals leads to an increase in pore connectivity, enhancing fluid transport in the reservoir (Farooq *et al*., 2024). However, in some cases, mineral precipitation may counteract this effect by clogging pore throats, reducing permeability in localized regions. Numerical simulations using the Lattice Boltzmann Method (LBM) and Finite Volume Method (FVM) confirm that dissolution-dominated systems experience overall permeability enhancement, while precipitation-dominated systems exhibit permeability reduction in certain zones. Experimental CO_2 injection studies highlight that the extent of pore structure modification depends on injection conditions. Higher CO_2 flow rates accelerate dissolution, leading to channel formation and an increase in reservoir permeability. Conversely, slow CO_2 injection rates promote more uniform mineral dissolution, resulting in gradual porosity evolution. Another critical factor influencing permeability changes is heterogeneity in the carbonate rock matrix. Carbonate reservoirs often exhibit varying mineral compositions, with regions of high dolomite content showing lower dissolution rates compared to calcite-rich areas (Onukwulu *et al*., 2023; Johnson *et al*., 2024). This leads to differential porosity evolution, affecting the overall hydraulic properties of the reservoir.

The geochemical and structural modifications induced by CO_2 injection have important implications for reservoir stability and the long-term security of CO_2 storage (Digitemie and Ekemezie, 2024). The dissolution of carbonate minerals can weaken the mechanical integrity of the rock, potentially leading to increased fracture formation and subsidence (Johnson *et al*., 2024). Geomechanical simulations indicate that high dissolution rates can create stress concentration zones, increasing the risk of mechanical failure in certain reservoir sections. However, some mineral precipitation processes can enhance mechanical stability by reinforcing the rock matrix (Anaba *et al*., 2023). These effects highlight the need for a balanced approach when designing CO_2 injection strategies to ensure structural integrity is maintained. Long-term CO_2 storage efficiency depends on the balance between mineral dissolution and precipitation. While dissolution increases porosity and enhances CO_2 storage capacity, excessive permeability alterations can lead to CO_2 leakage risks (Eyo-Udo *et al*., 2024). Sealing of pore spaces due to precipitation may trap CO_2 in certain zones, improving storage security. Thus, optimizing injection parameters such as pressure, flow rate, and temperature is essential for achieving stable and efficient CO_2 sequestration. Experimental and numerical findings demonstrate that CO_2-brine-rock interactions in carbonate reservoirs involve complex feedback mechanisms that influence geochemical evolution, pore structure changes, and reservoir stability. Understanding these processes is crucial for improving predictive models and designing effective CO_2 sequestration strategies that maximize storage capacity while minimizing risks associated with reservoir deformation and CO_2 leakage (Onukwulu *et al*., 2021; Basiru *et al*., 2023).

3. Conclusions and future directions

The review of pore-scale modeling of CO_2-brine-rock interactions in carbonate reservoirs has provided significant insights into the geochemical and geomechanical processes governing CO_2 sequestration. Experimental investigations using high-pressure flow cells and imaging techniques such as X-ray computed tomography (X-ray CT) and scanning electron microscopy (SEM) have demonstrated that CO_2 injection induces substantial mineral dissolution, particularly of calcite, leading to changes in pore structure and permeability. Numerical simulations using methods such as the Lattice Boltzmann Method (LBM) and the Finite Volume Method (FVM) have confirmed that the dissolution process enhances porosity and permeability in most cases, but mineral precipitation can locally clog pore spaces, reducing permeability in certain regions.

Geomechanical analyses indicate that excessive dissolution of carbonate minerals may weaken the reservoir rock, potentially leading to mechanical instability, while secondary mineral precipitation may counteract this effect in some cases by reinforcing the rock matrix. The dynamic interplay between these processes significantly influences the long-term security and efficiency of CO_2 storage in carbonate formations. This have important implications for large-scale CO_2 sequestration projects. Understanding the geochemical and geomechanical responses of carbonate reservoirs to CO_2 injection is critical for optimizing storage strategies and ensuring long-term stability. The increase in porosity and permeability due to dissolution enhances the potential storage capacity of carbonate reservoirs, but the formation of dissolution channels can also lead to preferential flow paths, increasing the risk of CO_2 leakage.

Additionally, mechanical stability remains a concern in large-scale CO_2 injection, as excessive dissolution can lead to loss of structural integrity, potentially causing subsidence or induced seismicity. Therefore, effective reservoir management strategies must consider controlled injection rates and pressure monitoring to mitigate these risks. Another key implication is the potential for mineral trapping of CO_2 through precipitation reactions. The formation of secondary minerals can enhance the long-term immobilization of CO_2, reducing the risk of leakage and improving storage efficiency. However, the spatial distribution of precipitation needs to be carefully monitored to prevent permeability reduction that could hinder further CO_2 injection.

Future research should focus on refining experimental and numerical methodologies to improve the accuracy of pore-scale models for CO_2-brine-rock interactions. Key areas for further investigation include, The development of real-time, high-resolution imaging techniques, such as synchrotron-based X-ray microtomography and in-situ Raman spectroscopy, can provide more detailed insights into the progression of dissolution and precipitation reactions at the pore scale. While pore-scale simulations provide detailed insights into geochemical and geomechanical interactions, integrating these models with reservoir-scale simulations is essential for predicting large-scale storage behavior. Hybrid modeling approaches that couple microscale processes with field-scale dynamics will enhance predictive accuracy.

Future studies should explore the long-term evolution of carbonate reservoirs post-injection. This includes examining the persistence of dissolution-induced permeability changes, the potential for delayed mineral precipitation, and the mechanical behavior of the reservoir over extended timescales. Research should focus on optimizing injection parameters, such as pressure, flow rate, and CO_2 purity, to maximize storage efficiency while minimizing risks associated with reservoir instability and leakage. Laboratory experiments should be designed to mimic in-situ reservoir conditions as closely as possible, including high-pressure, high-temperature environments, and the presence of multiple fluid phases. This will improve the reliability of experimental data for model calibration. By addressing these research gaps, future studies can enhance the understanding of CO_2 sequestration in carbonate reservoirs, contributing to the development of safe and efficient carbon storage solutions that support global climate mitigation efforts.

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