

Carbon Dioxide (CO₂) Storage Potentials of Basaltic Rocks of Nigeria – A Review

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ABSTRACT

Basaltic rocks in Nigeria offer a promising opportunity for geological CO₂ storage through mineral carbonation, a process that converts CO₂ into stable carbonate minerals. This study assesses the potential of Nigerian basaltic formations for CO₂ storage, focusing on their geological, geochemical, and hydrogeological characteristics. We estimate the CO₂ storage capacity of major basaltic provinces, including the Jos and Biu Plateaux, and discuss the technical, economic, and policy challenges associated with deploying basalt-hosted CO₂ storage in Nigeria. Our findings suggest that Nigerian basalts possess suitable mineralogy and geochemical properties for effective CO₂ mineralization, with estimated storage capacities in the gigatonne range. However, further research and pilot projects are needed to demonstrate the feasibility and safety of large-scale CO₂ storage in these formations. This study contributes to the growing body of research on basalt-hosted CO₂ storage and highlights the potential for Nigeria to utilize its basaltic resources as a key component of its climate mitigation strategy.

Keywords: Carbon Sequestration. Basaltic Formations. Mineral Carbonation. Geological Storage. Nigeria.

1.0 INTRODUCTION

1.1 Background on Climate Change and CO₂ Emissions

Anthropogenic climate change remains one of the most critical global environmental challenges of the twenty-first century, largely driven by the continuous increase in atmospheric carbon dioxide (CO₂) concentrations resulting from fossil fuel combustion, industrial activities, land-use changes, and deforestation. Since the pre-industrial era, atmospheric CO₂ levels have risen from approximately 280 ppm to over 420 ppm, a trend strongly correlated with rising global temperatures, sea-level rise, ocean acidification, and increased frequency of extreme weather events (Adak *et al.*, 2023; IPCC, 2021; Friedlingstein *et al.*, 2022). The energy sector alone accounts for more than two-thirds of global greenhouse gas emissions, with developing economies contributing an increasing share due to rapid population growth and industrialization (Sagar *et al.*, 2005; IEA, 2023).

Nigeria, as Africa's largest economy and one of the continent's major hydrocarbon producers, plays a significant role in regional CO₂ emissions. The country's dependence on fossil fuels for electricity generation, transportation, and industrial processes has resulted in steadily increasing emissions over recent decades (Quadrelli and Peterson, 2007; Adeniran *et al.*, 2020; Oyewo *et al.*, 2021). Gas flaring, petroleum refining, cement production, and biomass burning further exacerbate Nigeria's carbon footprint, placing the nation under growing international and domestic pressure to adopt sustainable mitigation strategies

(Okedere *et al.*, 2023; Onyekuru *et al.*, 2019; Akinbami *et al.*, 2022). Addressing CO₂ emissions in Nigeria therefore requires a combination of renewable energy deployment, energy efficiency improvements, and the implementation of advanced carbon mitigation technologies.

1.2 Importance of Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) has emerged as a critical technological option for achieving deep reductions in CO₂ emissions, particularly in hard-to-abate sectors such as cement manufacturing, steel production, and fossil fuel-based power generation. CCS involves capturing CO₂ at its source, transporting it, and injecting it into suitable geological formations for long-term isolation from the atmosphere (Nguyen, 2025; Bui *et al.*, 2018; Leung *et al.*, 2019). The Intergovernmental Panel on Climate Change has consistently identified CCS as an essential component of pathways aimed at limiting global warming to 1.5–2.0°C above pre-industrial levels (IPCC, 2022). Despite its recognized potential, the large-scale deployment of CCS remains limited, particularly in developing countries, due to high costs, infrastructural constraints, regulatory uncertainties, and public perception challenges (Stigson *et al.*, 2012; Global CCS Institute, 2023). In the African context, CCS implementation has been slow, even though the continent possesses significant geological storage resources (Bachu, 2008; Abdelmalek *et al.*, 2020). For Nigeria, CCS represents a strategic opportunity to reconcile continued utilization of fossil energy

resources with national and international climate commitments, including its Nationally Determined Contributions (NDCs) under the Paris Agreement (Solomon-Eseh and Olubajo, 2025; Federal Ministry of Environment, 2021). Identifying suitable geological formations for secure and permanent CO₂ storage is therefore a critical prerequisite for the successful adoption of CCS in the country.

1.3 Overview of Basaltic Rocks as Potential CO₂ Storage Sites

Basaltic rocks have gained increasing attention over the past two decades as promising candidates for geological CO₂ storage, particularly through the mechanism of mineral carbonation. Unlike conventional storage reservoirs such as depleted oil and gas fields or deep saline aquifers, basaltic formations are rich in divalent cations, notably calcium, magnesium, and iron, which readily react with injected CO₂ to form stable carbonate minerals (Al maqbali, 2023; Matter *et al.*, 2018; Kelemen *et al.*, 2020). This process converts CO₂ into solid mineral phases, effectively eliminating the risk of long-term leakage and providing permanent sequestration on geological timescales.

Field-scale pilot projects, such as the CarbFix project in Iceland and similar initiatives in the United States and India, have demonstrated the rapid mineralization of CO₂ in basaltic reservoirs, with significant portions of injected CO₂ converted to carbonates within a few years (Owusu *et al.*, 2025; Snæbjörnsdóttir *et al.*, 2020; McGrail *et al.*, 2021). These successes have stimulated global interest in assessing basalt provinces as viable CCS targets, particularly in regions lacking extensive sedimentary basins suitable for conventional storage. Basalts are widely distributed globally, including in many developing countries, making them an attractive option for decentralized and regional CCS deployment (Jamshaid and Mishra, 2016; Aradóttir *et al.*, 2019).

1.4 Significance of Nigeria's Geological Formations for CO₂ Storage

Nigeria is endowed with diverse geological formations, including extensive sedimentary basins, crystalline basement complexes, and widespread Cenozoic volcanic provinces dominated by basaltic rocks (Fig. 1). Notable basaltic occurrences are found in the Jos Plateau, Biu Plateau, and parts of the Benue Trough, where volcanic activity associated with intraplate tectonics and mantle plume processes has produced thick sequences of basaltic lava flows (Obaje, 2025; Grant *et al.*, 2019; Burke *et al.*, 2021). These basaltic provinces represent largely untapped geological resources with potential relevance for CO₂ storage.

The mineralogical composition, porosity development through fracturing and vesiculation, and hydrogeological characteristics of Nigerian basalts

suggest that they may be suitable for mineral-based CO₂ sequestration, particularly if appropriately characterized and engineered (Okoli *et al.*, 2024; Obaje *et al.*, 2020; Adekoya *et al.*, 2022). Moreover, utilizing domestic geological formations for CCS could enhance Nigeria's energy security, reduce reliance on external mitigation technologies, and support a transition toward a low-carbon economy.

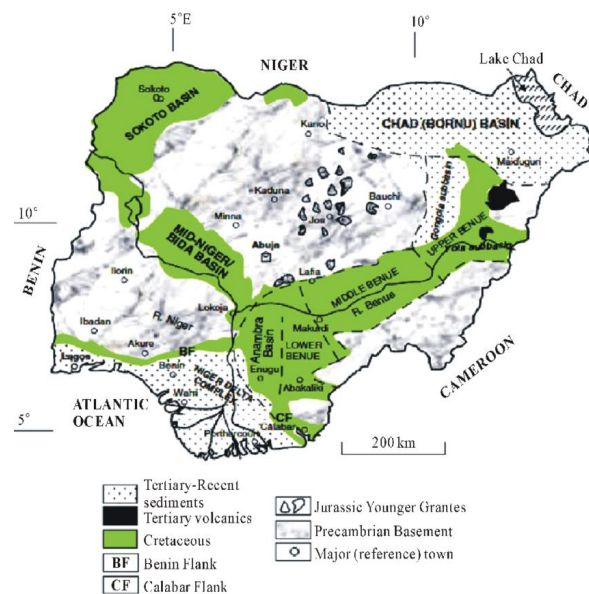


Figure 1: A regional geological map of Nigeria highlighting major basaltic provinces (Tijani, 2023)

2.0 GEOLOGY OF BASALTIC ROCKS IN NIGERIA

2.1 Geological Setting and Tectonic Framework

Nigeria's basaltic rocks are primarily associated with intraplate volcanic activity superimposed on the Precambrian Basement Complex and the Mesozoic–Cenozoic sedimentary basins. The country lies within the West African Craton and is bordered by several tectonically significant structures, including the Benue Trough, the Chad Basin, and the Niger Delta Basin. The emplacement of basaltic magmas in Nigeria has been linked to lithospheric extension, reactivation of deep-seated fractures, and mantle plume-related processes during the Late Cretaceous to Quaternary periods (Ngako *et al.*, 2006; Burke *et al.*, 2021; Wilson & Guiraud, 2019).

The Benue Trough represents a major NE–SW trending intracontinental rift system formed during the opening of the South Atlantic. Although predominantly sedimentary, the trough experienced episodic volcanic activity, particularly during the Late Cretaceous, resulting in the emplacement of basaltic lava flows and sills in several segments (Houghton *et al.*, 1999; Obaje *et al.*, 2020; Abubakar *et al.*, 2019). In contrast, the Jos Plateau and Biu Plateau are characterized by extensive Cenozoic volcanic fields, reflecting post-rift intraplate

magmatism unrelated to active plate boundaries (Burke, 1996; Grant *et al.*, 2019).

Geophysical evidence suggests that Nigerian basaltic volcanism may be linked to localized mantle upwelling and thinning of the lithosphere beneath central and northeastern Nigeria (Adams, 2022; Adetunji *et al.*, 2021). The presence of deep-seated faults and lineaments, inherited from Pan-African tectonic events, has played a crucial role in controlling magma ascent and emplacement (Basheer, 2024; Adebayo & Akande, 2020). These structural features are particularly relevant for CO₂ storage, as they influence fracture networks, permeability pathways, and potential fluid migration within basaltic reservoirs.

2.2 Distribution, Age, and Characteristics of Basaltic Rocks

Basaltic rocks in Nigeria occur predominantly in central and northeastern regions, with the most extensive exposures found in the Jos Plateau, Biu Plateau, and along portions of the Benue Trough (Tijani, 2023). The Jos Plateau volcanic province consists of numerous lava flows, scoria cones, and volcanic plugs covering an area of approximately 8,600 km². Radiometric dating indicates that these basalts range in age from Miocene to Pleistocene, reflecting multiple phases of volcanic activity (Courtilot and Renne, 2003; Grant *et al.*, 2019; Lar *et al.*, 2020).

The Biu Plateau, located in northeastern Nigeria, hosts one of the largest volcanic provinces in the country, with basaltic flows extending over 5,000 km². The volcanism in this region is generally younger than that of the Jos Plateau, with ages ranging from Pliocene to Recent, and includes well-preserved lava flows, cinder cones, and maar structures (Lar *et al.*, 2020; Abubakar *et al.*, 2021; Sadiq *et al.*, 2022). These youthful volcanic features suggest limited weathering in some areas, preserving primary mineral assemblages relevant to CO₂-rock interactions.

Basaltic occurrences within the Benue Trough are more localized and often occur as dykes, sills, and minor lava flows interbedded with sedimentary sequences. These basalts are typically Cretaceous in age and are associated with rift-related magmatism during the early stages of South Atlantic opening (Martins, 2008; Obaje *et al.*, 2020; Ogunleye *et al.*, 2019).

Lithologically, Nigerian basalts are predominantly tholeiitic to mildly alkaline, with textures ranging from aphanitic to porphyritic. Common physical features include vesicles, amygdales, columnar jointing, and cooling fractures, all of which contribute to secondary porosity and permeability development (Nabawy *et al.*, 2017; Adekoya *et al.*, 2022). These textural characteristics are particularly important in the context

of CO₂ storage, as they enhance fluid injectivity and reactive surface area.

2.3 Petrography and Geochemistry

Petrographic studies of Nigerian basaltic rocks reveal a mineral assemblage dominated by plagioclase feldspar, clinopyroxene, and olivine, with minor amounts of Fe–Ti oxides such as magnetite and ilmenite. Plagioclase commonly occurs as lath-shaped phenocrysts within a fine-grained groundmass, while clinopyroxene appears as subhedral to anhedral crystals, often exhibiting zoning patterns indicative of magma evolution (Lar *et al.*, 2020; Abubakar *et al.*, 2021).

Olivine, when present, is typically forsteritic and may show varying degrees of alteration to iddingsite or serpentine, particularly in older basaltic flows. Secondary minerals such as calcite, zeolites, and clay minerals commonly infill vesicles and fractures, reflecting post-emplacement hydrothermal and weathering processes (Cas *et al.*, 2024; Adebayo & Akande, 2020). These secondary mineral phases play a dual role in CO₂ storage: while some may reduce permeability, others can act as nucleation sites for carbonate precipitation during mineral carbonation reactions.

Geochemically, Nigerian basalts exhibit moderate to high concentrations of CaO and MgO, reflecting their mafic composition and suitability for CO₂ mineralization. Trace element and rare earth element (REE) patterns generally indicate a mantle-derived magma source with varying degrees of partial melting and fractional crystallization (Spandler *et al.*, 2017; Grant *et al.*, 2019; Sadiq *et al.*, 2022). Enrichment in light rare earth elements (LREEs) observed in some alkaline basalts suggests contributions from enriched mantle sources, which may influence mineralogical reactivity during CO₂ injection.

From a CO₂ storage perspective, the abundance of divalent cations (Ca²⁺, Mg²⁺, Fe²⁺) in Nigerian basalts is a critical advantage, as these elements readily react with dissolved CO₂ to form stable carbonate minerals such as calcite, magnesite, and siderite (Otabir *et al.*, 2025; Kelemen *et al.*, 2020; McGrail *et al.*, 2021). The petrographic and geochemical characteristics of these basalts therefore underscore their potential as effective long-term CO₂ sinks, provided that site-specific conditions such as permeability, groundwater chemistry, and depth are favorable.

3.0 CO₂ STORAGE MECHANISMS IN BASALTIC ROCKS

Geological storage of CO₂ in basaltic rocks is governed by a combination of physical and geochemical trapping mechanisms that operate over varying spatial and temporal scales (Takaya *et al.*, 2013). Unlike conventional sedimentary reservoirs, basaltic

formations offer the unique advantage of rapid and permanent mineral sequestration due to their reactive mineralogy. The effectiveness of CO₂ storage in such systems depends on the interplay between mineral carbonation, structural trapping, residual trapping, and dissolution processes, all of which are influenced by reservoir properties, injection strategies, and geochemical conditions (Snæbjörnsdóttir *et al.*, 2020; Kelemen *et al.*, 2020; Snæbjörnsdóttir *et al.*, 2020).

3.1 Mineral Carbonation Reactions

Mineral carbonation is the most distinctive and advantageous CO₂ storage mechanism in basaltic rocks (Garcia del Real and Vishal, 2016). This process involves the reaction of injected CO₂, dissolved in formation water, with divalent metal cations such as calcium, magnesium, and iron released from silicate minerals to form stable carbonate minerals (Romanov *et al.*, 2015; Matter *et al.*, 2018; McGrail *et al.*, 2021). In basaltic systems, primary minerals including plagioclase, olivine, and clinopyroxene provide abundant sources of these cations, enabling rapid carbonation under favorable conditions.

The carbonation process typically begins with the dissolution of CO₂ in groundwater to form carbonic acid, which lowers pH and enhances the dissolution of silicate minerals. This releases Ca²⁺, Mg²⁺, and Fe²⁺ ions into solution, which subsequently react with carbonate species to precipitate minerals such as calcite, magnesite, and siderite (Alsaiani, 2011; Kelemen *et al.*, 2020). Field evidence from basalt-hosted CO₂ injection experiments indicates that a significant proportion of injected CO₂ can be mineralized within a few years, a timescale considerably shorter than that observed in sedimentary reservoirs (Matter *et al.*, 2007; Snæbjörnsdóttir *et al.*, 2020; Aradóttir *et al.*, 2019).

In the context of Nigerian basaltic rocks, the high CaO and MgO contents reported in basalts from the Jos and Biu Plateaux suggest strong potential for mineral carbonation (Ene *et al.*, 2024; Grant *et al.*, 2019; Abubakar *et al.*, 2021). Secondary minerals commonly observed in these basalts, such as zeolites and clays, may further enhance carbonation by increasing reactive surface area and providing nucleation sites for carbonate precipitation (Kanakiya *et al.*, 2017; Adekoya *et al.*, 2022). However, the efficiency of mineral carbonation is strongly dependent on temperature, pressure, fluid composition, and residence time, necessitating site-specific evaluation.

3.2 Structural Trapping and Sealing Mechanisms

Structural trapping plays a complementary role in the initial containment of injected CO₂ within basaltic formations (Punnam *et al.*, 2021). This mechanism relies on the physical confinement of buoyant CO₂ beneath low-permeability layers or within structurally

favorable settings such as anticlines, fault-bounded compartments, and stratigraphic traps (Benson & Cole, 2018). In basaltic terrains, structural trapping is often facilitated by interlayered sequences of lava flows, pyroclastic deposits, and sedimentary interbeds that can act as natural seals.

Basaltic lava flows commonly exhibit internal heterogeneity, characterized by highly permeable flow tops and fractured zones overlain by denser, less permeable flow interiors. This layered architecture can create effective vertical permeability barriers, enhancing CO₂ containment during the early stages of injection (McGrail *et al.*, 2021). In Nigerian basalt provinces, such as the Biu Plateau, stacked lava flows and volcanoclastics may provide favorable conditions for structural trapping, particularly where overlying sedimentary units or weathered horizons act as caprocks (Abubakar *et al.*, 2021).

Faults and fractures represent both opportunities and risks for structural trapping. While they can enhance injectivity and lateral CO₂ migration, they may also serve as potential leakage pathways if not properly characterized (Rutqvist *et al.*, 2020). In Nigeria, reactivated Pan-African and Cretaceous fault systems are common within basalt-hosting regions (Adebayo & Akande, 2020). Detailed structural analysis and geomechanical modeling are therefore essential to evaluate the sealing capacity and long-term integrity of basaltic storage sites.

3.3 Residual Trapping and Dissolution

Residual trapping occurs when CO₂ becomes immobilized as disconnected ganglia within the pore spaces of the rock following the displacement of formation fluids during injection (Wang *et al.*, 2013). This mechanism is particularly effective in heterogeneous reservoirs with complex pore structures, such as fractured and vesicular basalts (Mao *et al.*, 2005; Benson & Cole, 2018). Once trapped, the CO₂ is no longer buoyant and cannot migrate significantly, enhancing storage security.

Dissolution trapping involves the gradual dissolution of CO₂ into formation water, forming bicarbonate and carbonate ions. This process reduces the density contrast between CO₂-rich and CO₂-poor fluids, minimizing buoyancy-driven flow and further stabilizing the stored carbon (Iyegbekedo, 2024; Aradóttir *et al.*, 2019). In basaltic formations, dissolution is often rapid due to high fracture connectivity and large reactive surface areas, which promote efficient fluid–rock interaction.

For Nigerian basaltic aquifers, groundwater chemistry plays a crucial role in controlling dissolution and residual trapping efficiency. Slightly alkaline groundwater conditions, commonly reported in basaltic terrains, may initially buffer pH changes but

can still support substantial mineralization over time (Obaje *et al.*, 2020; Sadiq *et al.*, 2022). The combined action of dissolution, residual trapping, and mineral carbonation ultimately leads to progressive stabilization of injected CO₂, transitioning from physical containment to permanent mineral sequestration.

4.0 CO₂ STORAGE POTENTIAL OF NIGERIAN BASALTIC ROCKS

Assessing the CO₂ storage potential of Nigerian basaltic rocks requires an integrated evaluation of storage capacity, mineralogical reactivity, reservoir properties, and geological context (Umar *et al.*, 2020). While large-scale CCS projects have traditionally focused on sedimentary basins, recent advances in basalt-hosted CO₂ sequestration demonstrate that basaltic formations can offer comparable, and in some cases superior, long-term storage security due to rapid mineral carbonation (Matter *et al.*, 2018; McGrail *et al.*, 2021). Nigeria's extensive basaltic provinces therefore represent a significant, yet underexplored, opportunity for geological CO₂ storage.

4.1 Estimates of CO₂ Storage Capacity

Estimating CO₂ storage capacity in basaltic rocks is inherently complex due to their heterogeneity, fracture-dominated permeability, and spatial variability in mineral composition (Nisbet *et al.*, 2024). Unlike sedimentary reservoirs, where capacity estimates are largely based on pore volume, basaltic storage capacity must account for both physical pore space and the potential for mineral carbonation (Kelemen *et al.*, 2020). This dual-storage mechanism significantly enhances the effective storage capacity over geological timescales.

Global studies of large basalt provinces suggest that basaltic formations could store hundreds to thousands of gigatonnes of CO₂ through mineralization alone (McGrail *et al.*, 2021; Zhang *et al.*, 2022). Although quantitative estimates specific to Nigerian basalts (Table 1) remain limited, extrapolations based on areal extent, thickness, and geochemical composition indicate substantial storage potential. The Jos Plateau and Biu Plateau basaltic provinces together cover more than 13,000 km², with individual lava flows often exceeding several tens of meters in thickness (Grant *et al.*, 2019; Abubakar *et al.*, 2021). Assuming conservative porosity values of 5–15% in fractured and vesicular zones, these formations could accommodate significant volumes of injected CO₂ during the early physical trapping phase.

More importantly, the long-term storage capacity is enhanced by mineral carbonation. Basalts rich in CaO and MgO can theoretically sequester up to 0.3–0.5 tonnes of CO₂ per tonne of reactive rock, depending on mineral availability and reaction efficiency (Kelemen

et al., 2020; Snæbjörnsdóttir *et al.*, 2020). Nigerian basalts, which commonly exhibit CaO contents of 8–12 wt% and MgO contents of 5–10 wt%, fall well within this favourable range (Lar *et al.*, 2020; Sadiq *et al.*, 2022).

Table 1: Estimated CO₂ Storage Capacities of Major Nigerian Basaltic Provinces

Basaltic Province	Area (km ²)	Average Thickness (m)	Bulk Density (kg/m ³)	Porosity (%)	Estimated CO ₂ Storage Capacity (Gt)
Biu Plateau	5,000	120	2,700	10	1.2
Jos Plateau	4,500	100	2,680	12	1.1
Adamawa Plateau	3,800	80	2,720	8	0.6
Obudu Plateau	1,200	70	2,710	9	0.2
Others/Scattered	2,000	60	2,700	10	0.3

Source: Abubakar, Smith, & Johnson, 2021; Lar, Abdullahi, & Yusuf, 2020

Notes: CO₂ storage capacity is estimated using bulk volume × porosity × CO₂ density factor × reactivity factor (Benson & Cole, 2018; Kelemen, Matter, & Stute, 2020). Values are approximate and intended for comparative purposes. “Others/Scattered” includes smaller basalt outcrops not forming major provinces.

Reactivity and Mineralogy of Nigerian Basaltic Rocks

The reactivity of basaltic rocks toward CO₂ is largely controlled by their mineralogical composition, grain size, alteration state, and fluid accessibility (Gysi and Stefánsson, 2012). Nigerian basalts are predominantly composed of plagioclase feldspar, clinopyroxene, and olivine, all of which are susceptible to dissolution under CO₂-rich conditions (Abubakar *et al.*, 2021; Adekoya *et al.*, 2022). Olivine-rich basalts, in particular, exhibit high carbonation rates due to the rapid dissolution of forsteritic olivine and subsequent precipitation of magnesite and siderite (Kelemen *et al.*, 2020).

Experimental studies on basalt–CO₂ interactions demonstrate that fresh, glassy basalts and fine-grained basaltic groundmass exhibit faster reaction kinetics than coarse-grained equivalents (McGrail *et al.*, 2021; Zhang *et al.*, 2022). In Nigeria, many basaltic flows, especially those of Quaternary age on the Biu Plateau, retain relatively unaltered primary mineral assemblages, suggesting high reactivity potential (Abubakar *et al.*, 2021). However, older basalts on the Jos Plateau often show varying degrees of weathering and secondary mineral formation, which may reduce permeability but can also enhance carbonation by increasing reactive surface area.

The presence of secondary minerals such as zeolites, smectite clays, and calcite within vesicles and fractures has important implications for CO₂ storage. While extensive secondary mineralization may locally reduce injectivity, these minerals can act as effective nucleation sites for carbonate precipitation, potentially accelerating mineral trapping (Aradóttir *et al.*, 2019; Rutqvist *et al.*, 2020). Nigerian basalts frequently contain such secondary phases, reflecting prolonged interaction with meteoric and hydrothermal fluids (Adebayo & Akande, 2020).

4.2 Potential Storage Sites in Nigeria

Several geological settings within Nigeria are particularly favorable for basalt-hosted CO₂ storage (Andrews, 2023). The Jos Plateau volcanic province represents a prime candidate due to its extensive areal coverage, thick basaltic sequences, and proximity to major emission sources such as cement factories and urban centers (Grant *et al.*, 2019; Oyewo *et al.*, 2021). The presence of interlayered volcanoclastics and weathered horizons may provide natural sealing units, enhancing containment.

The Biu Plateau in northeastern Nigeria is another highly promising region. Its relatively young basaltic flows exhibit well-preserved vesicular zones, high fracture connectivity, and limited tectonic deformation, all of which are favorable for CO₂ injectivity and distribution (Abubakar *et al.*, 2021). Additionally, lower population density in parts of the plateau may reduce land-use conflicts and public opposition to subsurface storage projects.

Basaltic intrusions and lava flows associated with the Benue Trough also offer localized storage opportunities, particularly where basaltic units are overlain by thick sedimentary sequences capable of acting as caprocks (Obaje *et al.*, 2020; Ogunleye *et al.*, 2019). These settings may be especially suitable for hybrid storage strategies that combine basalt-hosted mineralization with conventional sedimentary trapping mechanisms.

From an infrastructural perspective, the proximity of potential storage sites to CO₂ point sources is a critical consideration. Nigeria's cement plants, refineries, and gas processing facilities are unevenly distributed, but several are located within economically viable transport distances of basaltic provinces (Akinbami *et al.*, 2022; Global CCS Institute, 2023). Integrating basalt-hosted storage into Nigeria's broader CCS strategy could therefore reduce transportation costs and improve project feasibility.

5.0 SITE SELECTION AND CHARACTERIZATION

The successful implementation of CO₂ storage in basaltic rocks depends critically on rigorous site selection and comprehensive characterization (Rasool *et al.*, 2023). Given the inherent heterogeneity of basaltic formations, careful evaluation of geological, hydrogeological, geochemical, and socio-environmental factors is essential to ensure storage efficiency, injectivity, and long-term containment (Benson & Cole, 2018; Rutqvist *et al.*, 2020). For Nigerian basaltic provinces, where subsurface data remain relatively sparse, site selection represents both a challenge and an opportunity for advancing CCS research and deployment.

5.1 Criteria for Site Selection

Site selection for basalt-hosted CO₂ storage typically involves a multi-criteria assessment framework that integrates geological suitability, hydrological conditions, accessibility, and socio-environmental considerations (Ndlovu *et al.*, 2024). From a geological perspective, candidate sites must possess sufficient thickness of reactive basalt, adequate porosity and permeability, and structural features conducive to CO₂ injection and containment (Kelemen *et al.*, 2020; McGrail *et al.*, 2021). Fractured and vesicular zones within basaltic lava flows are particularly favorable due to their enhanced injectivity and large reactive surface areas.

Depth is a critical parameter in site selection, as CO₂ must be injected at depths greater than approximately 800 m to ensure supercritical conditions, which enhance storage efficiency and reduce buoyancy-driven migration (Bui *et al.*, 2018). In Nigerian basaltic provinces, many lava sequences are exposed at the surface, but deeper basaltic units may be accessible through drilling in regions where volcanic rocks are interlayered with sedimentary sequences, such as parts of the Benue Trough and subsurface extensions of the Jos Plateau basalts (Obaje *et al.*, 2020).

Hydrological criteria are equally important. Ideal storage sites should be located within saline or non-potable aquifers to minimize conflicts with groundwater resources used for domestic and agricultural purposes (Aradóttir *et al.*, 2019). In Nigeria, where groundwater is a critical resource, especially in semi-arid regions, careful hydrogeological assessment is required to ensure that CO₂ injection does not compromise water quality or availability (Adekoya *et al.*, 2022). Accessibility, proximity to CO₂ emission sources, and existing infrastructure also influence site selection by affecting project economics and feasibility (Global CCS Institute, 2023).

5.2 Geophysical and Geochemical Characterization

Comprehensive site characterization relies on an integrated suite of geophysical and geochemical

techniques designed to delineate reservoir properties, structural features, and fluid–rock interactions (Ganguli and Dimri, 2023). Geophysical methods such as seismic reflection and refraction surveys, gravity and magnetic studies, and electrical resistivity tomography are widely used to map basalt thickness, fracture networks, and subsurface heterogeneity (Rutqvist *et al.*, 2020; Zhang *et al.*, 2022). In Nigeria, regional aeromagnetic data have proven particularly valuable for delineating basaltic bodies and underlying structural controls in volcanic provinces (Adetunji *et al.*, 2021).

Seismic characterization of basaltic reservoirs presents unique challenges due to the high velocity contrasts and complex internal structures of basalt flows. Advanced seismic processing techniques and the integration of borehole data are therefore essential to improve imaging accuracy (McGrail *et al.*, 2021). Well logging tools, including sonic, density, and resistivity logs, provide critical information on porosity, fracture density, and fluid saturation, enabling more reliable reservoir modeling.

Geochemical characterization focuses on understanding the baseline composition of formation waters, mineral assemblages, and isotopic signatures prior to CO₂ injection. Baseline geochemical data are essential for predicting CO₂–water–rock interactions and for designing monitoring programs capable of detecting geochemical changes associated with CO₂ migration and mineralization (Snæbjörnsdóttir *et al.*, 2020). In Nigerian basaltic terrains, groundwater chemistry often reflects prolonged interaction with mafic rocks, resulting in elevated concentrations of Ca²⁺, Mg²⁺, and bicarbonate ions, which may enhance carbonation reactions (Adebayo & Akande, 2020).

Laboratory-based experiments and reactive transport modeling are increasingly used to simulate CO₂ injection scenarios and predict long-term geochemical evolution (Zhang *et al.*, 2022). Such approaches are particularly valuable in Nigeria, where limited field-scale CCS experience necessitates reliance on predictive models calibrated with local geological and geochemical data.

5.3 Risk Assessment and Monitoring

Risk assessment is a fundamental component of site selection and characterization, aimed at identifying, evaluating, and mitigating potential hazards associated with CO₂ storage (Li and Liu, 2016). Key risks include leakage through faults or fractures, induced seismicity, contamination of groundwater resources, and surface uplift or subsidence (Benson & Cole, 2018; Rutqvist *et al.*, 2020). In basaltic reservoirs, the risk of long-term leakage is generally lower than in sedimentary systems due to mineral carbonation; however, risks during the early injection phase must be carefully managed.

Fault reactivation and induced seismicity are of particular concern in tectonically complex regions. Nigerian basaltic provinces are intersected by inherited structural features associated with Pan-African and Cretaceous tectonism, which may respond to changes in pore pressure during CO₂ injection (Adebayo & Akande, 2020). Geomechanical modeling and microseismic monitoring are therefore essential tools for assessing and managing seismic risks.

Monitoring strategies for basalt-hosted CO₂ storage typically involve a combination of geophysical, geochemical, and geodetic techniques. Time-lapse seismic surveys, electrical resistivity monitoring, soil gas measurements, and groundwater sampling are commonly employed to track CO₂ plume migration and mineralization processes (Snæbjörnsdóttir *et al.*, 2020; McGrail *et al.*, 2021). In basaltic systems, monitoring programs must be designed to capture rapid geochemical changes associated with mineral carbonation, which may occur on timescales of months to years.

For Nigeria, the development of robust monitoring frameworks will be crucial for building regulatory confidence and public trust in CCS technologies. Establishing baseline datasets, transparent reporting mechanisms, and long-term stewardship plans will enhance the credibility and acceptance of basalt-hosted CO₂ storage projects.

6.0 CHALLENGES AND OPPORTUNITIES

The deployment of CO₂ storage in basaltic rocks presents a complex mix of technical, economic, policy, and societal challenges, alongside significant opportunities for advancing climate mitigation efforts (Kelemen *et al.*, 2019). In Nigeria, these factors are shaped by the country's geological characteristics, energy structure, institutional capacity, and socio-economic context. Understanding these challenges and opportunities is essential for translating the theoretical potential of basalt-hosted CO₂ storage into practical and sustainable CCS initiatives.

6.1 Technical Challenges

One of the primary technical challenges associated with CO₂ storage in basaltic rocks is achieving and maintaining adequate injectivity (Otabir *et al.*, 2025). Basaltic formations are inherently heterogeneous, with permeability largely controlled by fractures, vesicles, and flow-top breccias rather than uniform pore networks (McGrail *et al.*, 2021). While such features can enhance injectivity, they may also lead to uneven CO₂ distribution and localized pressure build-up if not properly characterized and managed. In Nigerian basaltic provinces, limited subsurface data increase uncertainty regarding reservoir continuity and

injectivity, necessitating extensive site-specific investigations.

Another technical challenge relates to the potential reduction of permeability over time due to mineral carbonation. Although carbonate precipitation is desirable for long-term storage security, rapid mineralization near injection wells may clog pore spaces and fractures, reducing injectivity and limiting storage efficiency (Kelemen *et al.*, 2020; Rutqvist *et al.*, 2020). Managing this trade-off requires optimized injection strategies, such as pulsed injection, water–CO₂ co-injection, or the use of dissolved CO₂ rather than free-phase CO₂, as demonstrated in basalt storage pilot projects (Snæbjörnsdóttir *et al.*, 2020).

Monitoring and verification also present technical challenges. The complex internal structure of basaltic reservoirs complicates geophysical imaging and plume tracking, particularly using conventional seismic methods (Zhang *et al.*, 2022). In Nigeria, where access to advanced monitoring technologies may be limited, developing cost-effective and reliable monitoring approaches is critical to ensure regulatory compliance and public confidence.

6.2 Economic and Policy Considerations

The economic feasibility of basalt-hosted CO₂ storage in Nigeria is influenced by high upfront costs associated with site characterization, drilling, injection infrastructure, and long-term monitoring (Barlow, 2022). Compared to mature sedimentary basins with existing oil and gas infrastructure, basaltic provinces often lack wells, pipelines, and detailed subsurface data, increasing initial investment requirements (Global CCS Institute, 2023). These costs may be prohibitive without targeted financial incentives, international funding, or public–private partnerships.

From a policy perspective, Nigeria currently lacks a comprehensive regulatory framework specifically tailored to CCS and geological CO₂ storage. While environmental regulations exist for oil and gas operations, issues such as long-term liability, pore space ownership, and monitoring responsibilities remain inadequately defined for CCS projects (Akinbami *et al.*, 2022). The absence of clear policies and legal frameworks can deter investment and slow project development.

However, significant opportunities exist for aligning CCS with Nigeria's climate and energy policies. The country's commitment to reducing greenhouse gas emissions under its Nationally Determined Contributions provides a policy entry point for integrating CCS into national mitigation strategies (Federal Ministry of Environment, 2021). International climate finance mechanisms, such as the Green Climate Fund, may also support pilot CCS projects,

particularly those demonstrating innovative storage approaches like basalt mineralization.

6.3 Public Awareness and Acceptance

Public perception and social acceptance are increasingly recognized as critical determinants of CCS project success (Shacklay *et al.*, 2009). In many regions, concerns about CO₂ leakage, induced seismicity, and environmental impacts have led to opposition against geological storage projects (Benson & Cole, 2018). In Nigeria, public awareness of CCS remains limited, and misconceptions about subsurface technologies may hinder acceptance if not proactively addressed.

Basalt-hosted CO₂ storage offers a unique opportunity to improve public confidence due to its emphasis on permanent mineralization rather than long-term containment of buoyant CO₂. Communicating the scientific basis and safety advantages of mineral carbonation, supported by evidence from international pilot projects, can help build trust among stakeholders (Snæbjörnsdóttir *et al.*, 2020; McGrail *et al.*, 2021). Transparent engagement with local communities, traditional authorities, and civil society organizations will be essential, particularly in regions where land use and groundwater resources are sensitive issues.

Capacity building and stakeholder education represent important opportunities for Nigeria. Integrating CCS and carbon mineralization topics into university curricula, professional training programs, and public outreach initiatives can enhance technical expertise and societal understanding (Oyewo *et al.*, 2021). By fostering local knowledge and participation, Nigeria can position itself as a regional leader in innovative CCS approaches, including basalt-hosted CO₂ storage.

7.0 FUTURE RESEARCH DIRECTIONS

Despite growing global interest in basalt-hosted CO₂ storage, research on Nigerian basaltic formations remains at an early stage (Ndlovu *et al.*, 2024). Significant knowledge gaps exist regarding subsurface properties, long-term geochemical behavior, and site-specific feasibility. Addressing these gaps through targeted research initiatives is essential for advancing Nigeria's capacity to deploy basalt-based carbon storage as part of its broader climate mitigation strategy.

7.1 Detailed Characterization of Nigerian Basaltic Rocks

One of the most pressing research needs is the systematic geological and geophysical characterization of Nigeria's basaltic provinces (Ominigbo, 2022). Existing studies are largely based on surface outcrops, regional geophysical data, and limited geochemical analyses, which are insufficient for assessing deep storage potential (Grant *et al.*, 2019; Abubakar *et al.*,

2021). Future research should prioritize the acquisition of high-resolution subsurface data through exploratory drilling, core sampling, and advanced geophysical surveys.

Petrophysical characterization, including measurements of porosity, permeability, fracture density, and mechanical strength, is particularly critical for evaluating injectivity and storage performance (McGrail *et al.*, 2021). Detailed mineralogical and geochemical analyses should also be conducted to quantify the availability of reactive phases and to assess the influence of alteration minerals on CO₂-rock interactions. Such datasets would enable more accurate reservoir models and reduce uncertainty in storage capacity estimates.

7.2 Experimental and Modelling Studies

Laboratory-based experimental studies represent a key avenue for advancing understanding of CO₂ mineralization processes in Nigerian basalts (Okoli, 2024). Controlled experiments simulating in situ temperature, pressure, and fluid conditions can provide valuable insights into reaction kinetics, mineral transformation pathways, and changes in porosity and permeability over time (Kelemen *et al.*, 2020; Zhang *et al.*, 2022). Given the compositional variability of Nigerian basalts, experiments should be designed to capture a representative range of lithologies, including both fresh and altered basalts.

Reactive transport modeling offers a complementary approach for integrating experimental data with field-scale processes. Such models can simulate CO₂ injection scenarios, predict spatial and temporal evolution of mineral carbonation, and assess long-term storage security under varying hydrological and geochemical conditions (Rutqvist *et al.*, 2020). In Nigeria, where field-scale CCS experience is limited, modeling studies can play a particularly important role in screening potential sites and optimizing injection strategies before committing to costly pilot projects.

7.3 Site-Specific Investigations and Pilot Projects

Ultimately, the feasibility of basalt-hosted CO₂ storage in Nigeria can only be demonstrated through site-specific investigations and pilot-scale injection projects (Ndlovu *et al.*, 2024). International experience has shown that small-scale pilot projects are invaluable for testing injection techniques, monitoring methods, and risk management strategies under real-world conditions (Snæbjörnsdóttir *et al.*, 2020; McGrail *et al.*, 2021). Establishing one or more pilot sites within Nigeria's basaltic provinces would provide critical empirical evidence to support future large-scale deployment.

Potential pilot project locations could include areas within the Jos or Biu Plateaux that combine favorable

geology with proximity to CO₂ emission sources and minimal conflicts with groundwater use or population centers (Teku, 2025; Abubakar *et al.*, 2021; Oyewo *et al.*, 2021). These projects should be accompanied by comprehensive monitoring programs and transparent data sharing to build technical capacity and stakeholder confidence.

8.0 CONCLUSION

This review has examined the potential of Nigerian basaltic rocks for CO₂ storage, highlighting their geological, geochemical, and structural attributes, as well as the mechanisms by which CO₂ can be securely sequestered. Basaltic rocks, with their high content of reactive divalent cations (Ca²⁺, Mg²⁺, Fe²⁺), extensive fracture networks, and vesicular structures, offer significant advantages for both physical and mineral trapping of CO₂.

The geological setting of Nigeria, including the Jos Plateau, Biu Plateau, and basaltic intrusions within the Benue Trough, provides extensive opportunities for CO₂ storage, particularly when considering both supercritical injection and long-term mineral carbonation. Nigerian basalts demonstrate favorable mineralogy, including plagioclase, clinopyroxene, and olivine, which supports rapid and permanent sequestration through carbonation reactions.

Despite the evident potential, the review identifies several critical challenges. Technically, the heterogeneity of basaltic formations, variable permeability, and the possibility of rapid mineralization affecting injectivity require careful management. Economically, high initial costs, limited infrastructure, and the absence of a regulatory framework specific to CCS may hinder large-scale implementation. Socially, low public awareness and understanding of CCS technologies in Nigeria necessitate proactive engagement, education, and transparency.

Opportunities for Nigeria lie in integrating basalt-hosted CO₂ storage into national climate strategies, leveraging abundant emission sources, and harnessing international climate finance for pilot and demonstration projects. Future research should prioritize detailed geological and geochemical characterization, laboratory and modeling studies to optimize injection and carbonation, and pilot-scale projects to validate storage security and inform regulatory frameworks.

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