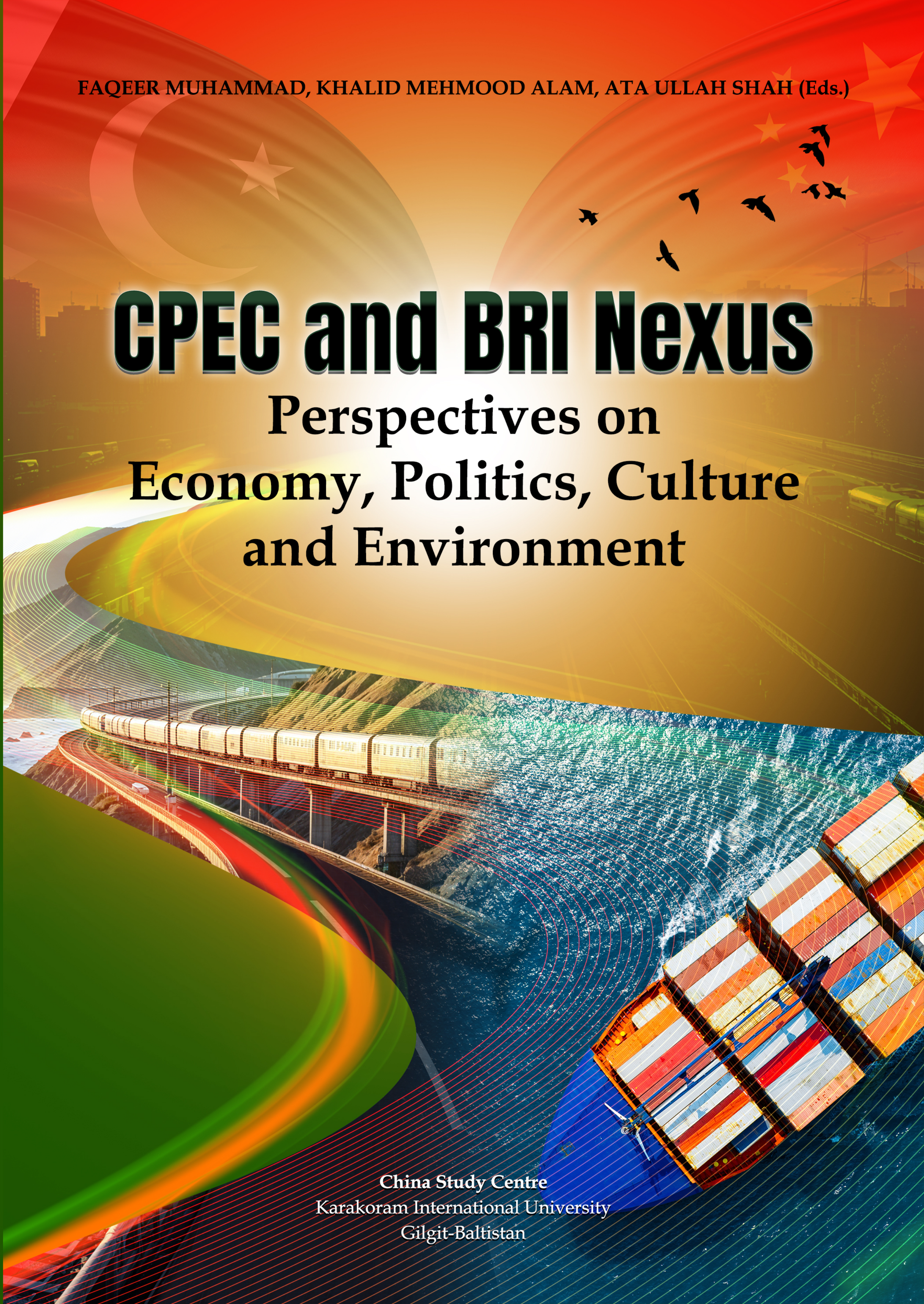

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CPEC and BRI Nexus

Perspectives on Economy, Politics, Culture and Environment

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Developing a Roadmap for Implementing Mineral Carbonation as a CO2 Capture Solution for Climate Change Mitigation in Belt and Road Initiative Projects

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Abstract

The Belt and Road Initiative (BRI), spearheaded by China, is a sweeping endeavor with the potential to significantly impact global infrastructure, economic growth, and regional connectivity. With its extensive network spanning 138 countries, the BRI promises substantial economic benefit. However, concerns have been raised over its potential environmental ramifications, particularly its contribution to climate change through significant CO_2 emissions. Serious global climate change and warming challenges are being addressed through multiple means of Carbon Dioxide (CO_2) sequestration (the process of capturing and storing CO_2). Various mature techniques for CO_2 sequestration are used globally. One of the potential CO_2 sequestration options is ex situ and in situ mineralization in mining tailings (waste) and geological formations. By recognizing the urgency to deal with these environmental challenges, there is a need for a detailed investigation of mineral carbonation and the geological sequestration of mafic and ultramafic rocks and mine tailings. To address this environmental concern in terms of CO_2 emissions from BRI projects, a comprehensive roadmap advocating the adoption of mineral carbonation as a CO_2 capture solution for climate change mitigation in **Belt and Road initiative projects** is proposed in this study.

Keywords: BRI, mineral carbonation, climate change, carbon capture utilization and storage (CCUS)

Introduction

Belt and road initiative (BRI) is a billion of dollars mega project, proposed by China in 2013 with an aim to connect Asia to Africa and Europe via sea and land (Schulhof et al., 2022). This project is described as the largest project in terms of infrastructure in the whole human history with an investment of more than US$ 8000 billion with directly involvement of world's half population (Williams et al., 2020). This project is signed by about 130 countries and 30 international organizations received US$ 90 billion in Chines Foreign Direct Investment (FDI) with an exchange of US$ 6 trillion in trade with China (CHINA, 2023).

This project aims to two new commercial corridors linking China to other parts of globe, reshaping economic geography in Central Asia and beyond (Bird et al., 2020). The BRI involves revitalizing ancient overland trading routes termed as the Silk Road Economic Belt and establishment of new sea corridors along the old Marco Polo road, spanning Africa, Southeast Asia, and Europe (Zhao, 2020). So, we can say that this project is an extension of the ancient corridor that once linked China with west, Ibn Battuta's and Marco Polo routes in the north as well as southern sea routes explored by Ming dynasty admiral Zheng He during his maritime expeditions. The BRI now refers to the whole geographical region of the well know "Silk Road" trade route (*Scholar*, n.d.). Key elements of this include promoting economic growth, stimulating economies in regions historically lagging behind, encouraging businesses to compete for BRI contracts, and fostering interdependent markets for China (Duarte et al., 2023). The initiative also focuses on developing high-technology industries globally and is aiming to promote the development of infrastructure like railways, ports, roads, airports etc., alongside energy projects like power stations and pipelines, and telecommunications networks (Mitrovic, 2016). Through the BRI, China seeks to secure its borders on the Asian mainland, facilitate trade and infrastructure development, and create partnerships with countries along the proposed routes (Liu & Dunford, 2016). The scale of the BRI is unprecedented in modern history, with investments anticipated to surpass several trillion dollars over the coming decades, aims to connect around 60% of the global population through infrastructure development with "win-win partnerships"(Parks et al., 2023). It represents the largest infrastructure and investment project in history, dwarfing the Marshall Plan in its ambition and scope.

Table 1: Countries (excluding Palestine) participating in BRI

Locations	**Countries number**
Sub-Saharan Africa	44
Europe & Central Asia	34
East Asia & Pacific	25
Latin America & Caribbean	22
Middle East & North Africa	19
South East Asia	6
Total	150
EU	17
G20	8

In total, there are 150 countries (excluding Palestine) involved in BRI initiative. Among them, 17 are EU countries and 8 are G20 countries.

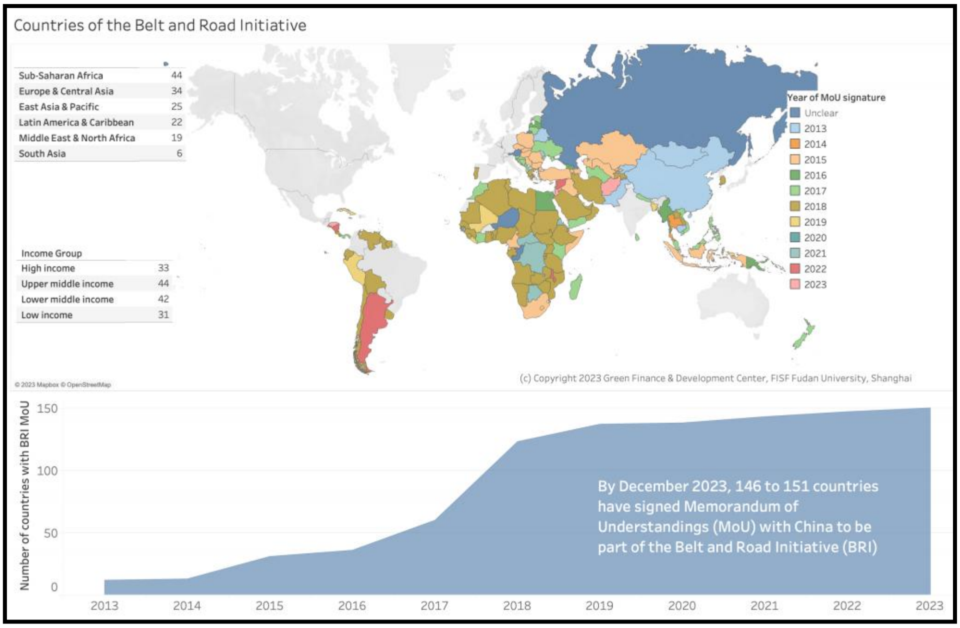


Figure 1: Nations for collaboration within BRI (WANG, 2023)

Land Corridors of BRI (Teotia, 2023)

1) **New Eurasian Land Bridge:** This route runs through Kazakhstan, Russia, Belarus, Poland, and Germany, and China's Xinjiang Autonomous Region, links Western China and western Russia

2) **China–Central Asia–West Asia Corridor:** Extends via Western China to Turkey, facilitating economic connectivity across Central and West Asia.

3) **China-Indochina Peninsula Economic Corridor:** Connects Southern China to Singapore, enhancing economic ties and infrastructure development in the region.

4) **Trans-Himalayan Multi-Dimensional Connectivity Network:** Aims to transform Nepal a land-linked country from a landlocked, improving connectivity and trade opportunities.

5) **Northern China to Russian Far East Corridor:** This route extends from Northern China via Mongolia to Russia far East with the Russia-China Investment Fund

6) **China–Pakistan Economic Corridor (CPEC):** this is a significant component closely resemblance to the BRI, involving a $62 billion investment in infrastructure projects in Pakistan. It focuses on

modernizing the economy, transportation and energy infrastructure. CPEC became partially operational in 2016 with Chinese cargo reaching Gwadar Port for further shipment to West Asia and Africa. The infrastructure at provides alternative routes that are not reliant on Malacca strait (S. M. Ali & Ali, 2020).

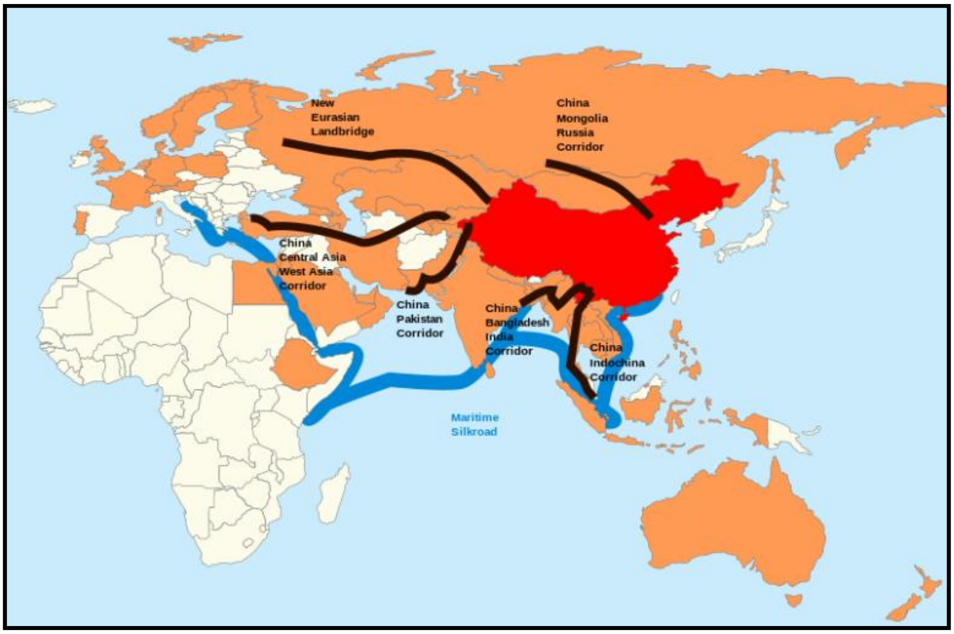


Figure 2: Routes connecting China and BRI member regions (Teotia, 2023)

Possible environmental challenges in China and BRI countries

The BRI is a massive undertaking with the aim of promoting regional connectivity and economic growth across a population of 4.4 billion (Ge et al., 2018). This endeavor represents the largest infrastructure investment in recent history, totaling trillions of dollars for infrastructure development including transportation network, technical capacity building, telecommunications, energy, and industrial capacity (Liu & Dunford, 2016). On one hand BRI promises significant advantages, but in other hand it presents considerable environmental risks and challenges, ranging from immediate biophysical impacts to long-lasting negative consequences resulting from unsustainable infrastructure, technology, and resource extraction (Messerli et al., 2019). The BRI's vast scope and scale have significant environmental implications, including habitat destruction, pollution, increased carbon emissions, and systemic issues that may arise from locking countries into unsustainable development paths (Ahmad et al., 2020). It is crucial to consider that the first step of BRI framework involves constructions, including rail lines, roads, airports, industrial parks, seaports and similar more projects, which will be responsible for environmental disturbance directly or indirectly (Losos et al., 2019). Such type of mega projects is full of uncertainties and risks, producing significant volumes of waste and harmful emissions that pose a threat to the ecosystem.

According to World Bank analysis on the environmental impact of BRI "such huge transportation infrastructure will expose local communities and regions to social and environmental threats as BRI routes crosses through them and this initiative can increase carbon dioxide (CO_2) emission 7% in total" (Chin et al., 2024). Additionally the reports predicted that BRI transport infrastructure will raise CO_2 emission by 0.3 percent globally and more than 7% in some regions (Ruta et al., 2019)(Losos et al., 2019).

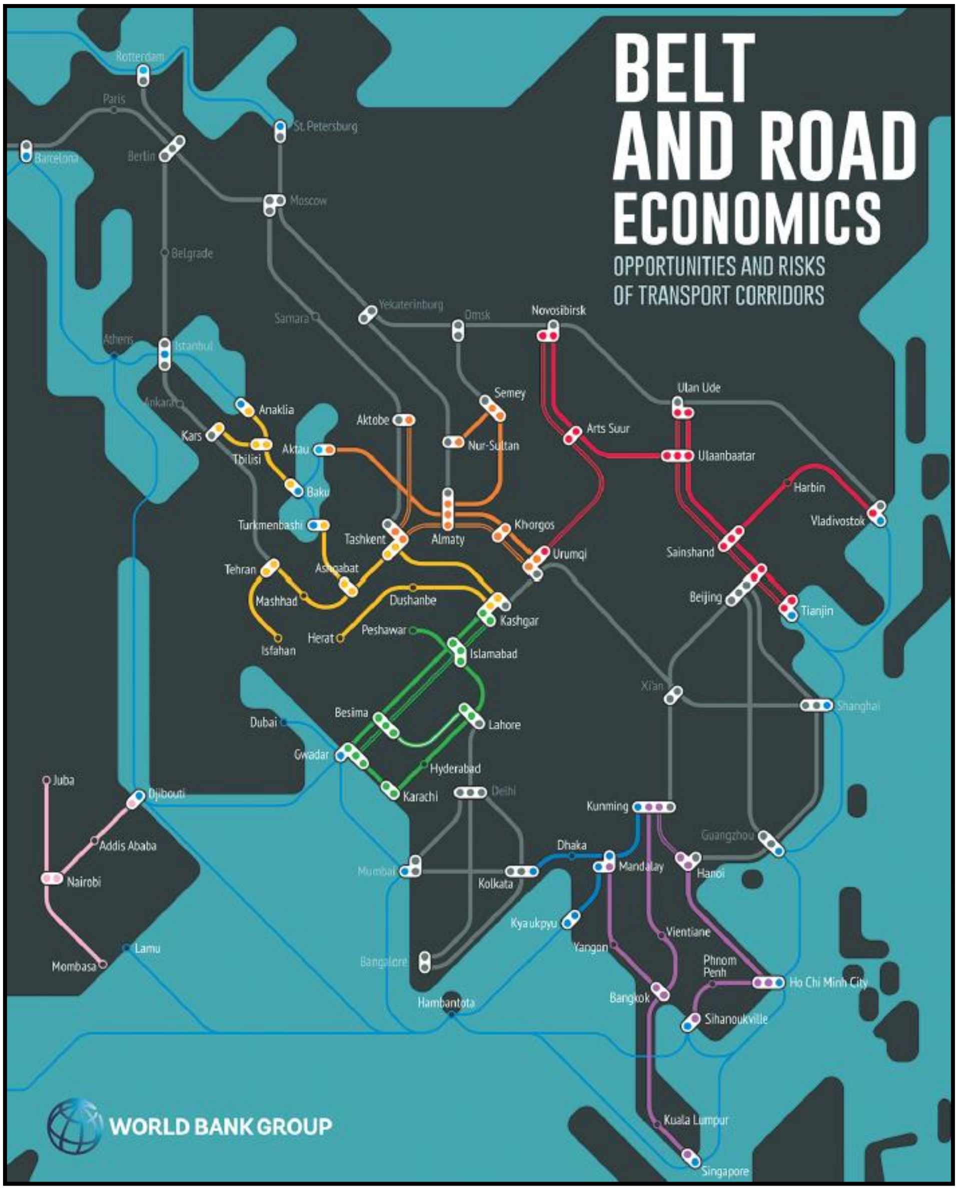


Figure 3; Six terrestrial routes of the Silk Road Economic Belt (Ruta et al., 2019)

Given the challenge of coal-fired electricity generation's dominance in China and 138 BRI countries, innovative approaches must be considered to achieve the goal of BRIGC or The Coalition. As climate change is a top priority of the ruling party in Chinese government so in 2020, China's president put forward " carbon peaking and neutrality before 2030" and “to achieve carbon neutrality up to 2060" (Cheshmehzangi & Chen, 2021). China is the largest CO_2 producer in the whole world, having half of the world's coal power plants located within its borders (Lindner et al., 2013). Moreover, China ranks as fifth-largest producer of oil and the second-largest its consumer, along with serving as largest contributor to worldwide demand for gas (J. Zhang, 2015). In 2019, foreign direct investment (FDI) in China totaled $138 billion, compared to $135 billion in 2018. Of this, 1.6% was directed towards the mining sector, and 25.6% towards the manufacturing sector (ESCAP, 2021). In 2019, the mining and manufacturing sectors employed 3.7 million and 38.3 million people, respectively, which represented 2.1% and 22.3% of total employment in the country (LANKA, n.d.).

BRI International Green Development Coalition (BRIGC)

President Xi Jinping announced the formation of the BRI International Green Development Coalition (BRIGC) during the first Belt and Road Forum for International Cooperation (BRF) in May 2017 (K. Chen, 2024). It was formally inaugurated during the Thematic Forum of the second BRF in April 2019. The main goals of BRIGC are to integrate environmentally sustainable practices into the BRI, promoting global agreement on the Green Belt and Road, and to help in achieving the 2030 Sustainable Development Goals (Cao et al., 2024). BRIGC presently boasts more than 130 partners, encompassing 25 environmental departments from various countries, international organizations, research institutions, and businesses(Geraci et al., 2020). It offers platforms for policy discussions, sharing of knowledge, transfer of green technology, and thematic activities that concentrate on global climate change governance and the promotion of environmentally-friendly practices (Geraci et al., 2020).

Many Sustainable Development Goals (SDGs), such as SDG2 (Zero Hunger), SDG3 (Good Health and Well-Being), SDG5 (Gender Equality), and SDG7 (Affordable and Clean Energy), are impacted by *BRIGC's* work (S. Ali et al., 2018). With an emphasis on participating nations in the BRI, the coalition consults with stakeholders on terms of reference and subject areas. Partners participate in core activities related to climate change governance and green transformation through policy dialogues, research projects, capacity building initiatives, and pilot projects (Baruah & Nath, 2019). The initiative aligns with the Climate Action Summit work stream by addressing thematic fields such as green finance, green energy, energy efficiency, environmental quality advancement, green cities, corporate social responsibility, and technology innovation. BRIGC collaborates with renowned institutions and experts on climate change, funding thematic activities through voluntary donations from partners. Stewardship is managed by Co-Chairs, a Consultation Committee, and a Secretariat. Communication strategies involve cooperation with existing bilateral and multilateral mechanisms.

Green Silk Road initiative

BRI includes the Green Silk Road initiative, which focuses on promoting eco-friendly and sustainable practices in all BRI activities (L. Wang & Cheng, 2024). Advocating for recyclable, low-carbon, and sustainable lifestyle, this initiative, emphasized by Xi Jinping, aims to integrate sustainability into daily work and practices to achieve the UN SDGs by 2030 (Yang, 2021). The Green Silk Road initiative is recognized as a viable solution to improve the adoption of UN's 2030 Agenda for Sustainable Development, aligning global sustainability goals. Described as a sustainability-focused subtheme of the BRI, the "green silk road" aims to enhance Beijing's environmental credentials and promote sustainable practices within the initiative (Lewis et al., 2021). The Green Silk Road is acknowledged as a crucial tool to steer towards a new pathway of sustainable development, moving away from past environmental challenges (Thees, 2020). The Green Silk Road initiative is part of China's ambitious BRI, emphasizing sustainable practices and environmental considerations in infrastructure development. Sources collectively emphasize the significance of the Green Silk Road initiative in promoting environmental sustainability and eco-friendly practices within the broader BRI framework (*No Title*, n.d.).

Objectives of proposed roadmap

The objective of this roadmap is to offer a sustainable road map solution for the ecological impact of the BRI on the world's climate by contributing to the ongoing literature and debates. The specific focus is to explore mineral carbonation, both in-situ and ex-situ, as well as geological carbonation, and imply possible green technologies and policies to BRI's collaborated countries to deal with the negative impact of the project on climate change and greenhouse gas emissions, which are associated with billions of dollars in investment. In short, while Belt and Road Initiative (BRI) projects have undeniably driven economic growth, the associated rise in CO_2 emissions necessitates robust and sustainable solutions. Among the promising approaches, mineral carbonation offers a unique opportunity to permanently store captured CO_2, mitigating long-term climate change impacts. However, for the implementation and adoption of mineral carbonation strategy with BRI framework, many several knowledge gaps are needed to evaluate.

Carbon capture, utilization and storage, CCUS technology and Green BRI

The use of CCUS technique to achieve large-scale and stable storage of CO_2 in a short period is the most effective way to solve the carbon emissions of key industries (Sanna et al., 2014). Among all the CO_2 sequestration techniques, mineral carbonation is the most reliable as it provides safe and permanent disposal of CO_2 into stable minerals without any requirement for long-term monitoring (Qian et al., 2024). The idea of CO_2 mineralized storage was proposed in 1990s by Seifritz, a technique that mimics the natural weathering process of rocks; CO_2 then reacts with hydroxides, oxides, silicates, calcium and magnesium to form stable carbonates with permanent storage of CO_2 (Seifritz, 1990) . Mineral carbonation and geological sequestration methods have the potential to overcome climate change challenges. Mineral trapping of CO_2 turns it into solid and stable carbonate minerals (Snæbjörnsdóttir et al., 2020). CO2 interacts and reacts with the minerals present in mafic and ultramafic rock formations. CO_2 becomes part of the rock as a new and stable carbonate mineral through geochemical reactions at molecular level (Sturmer et al., 2020).

There is a huge variety and availability of geological sequestration options globally [15, 16]. A map of CO_2 sequestration pilot projects, facilities, and long-term carbon storage potential in geological formations within BRI partner countries is presented in Figure 1 (Zanoletti et al., 2018). Some of the global prospective locations and the corresponding rock types suitable for geological sequestration and mineral carbonation are,

- **Iceland:** Reactive Basalt (e.g., CarbFix project) has already capture 80,000 tons of CO_2 since 2012 of its commencement taking less than 2 years of mineral carbonation.
- **Washington State:** Wallula project (Continental Flood Basalt),
- **India:** Deccan traps (Continental Basaltic Lava),
- **Cyprus, Oman and Turkey**: Troodos, Kizildag, and Semail ophiolites (Reactive Peridotite Intrusions) and
- **Portugal:** Gabbros and Sines sub-volcanic massif (Peridotites).

Most of these projects are in the BRI partner countries so the CO_2 sequestration of these plants can be enhanced by more investment for their upgradation to mitigate the climate issues due to BRI project.

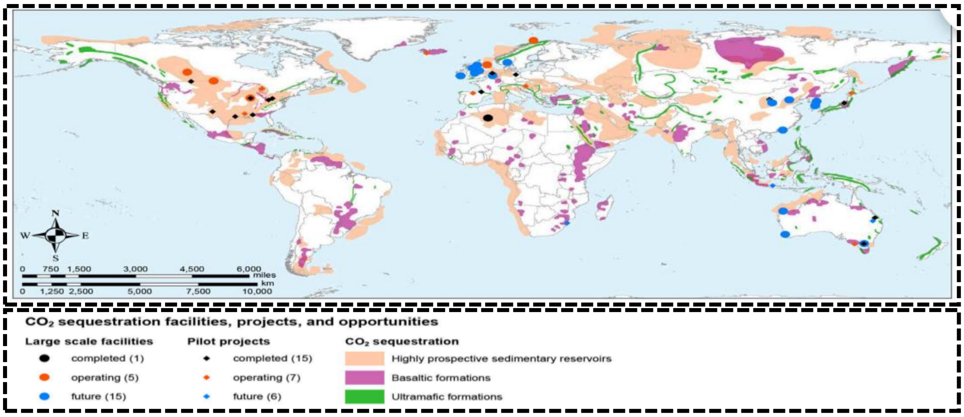


Figure 4; Map of pilot projects and CO_2 sequestration facilities, and long term storage potential in geological formations in different BRI regions of world (P. Kelemen et al., 2019) (P. B. Kelemen et al., 2011)

Proposed In-situ CO_2 sequestration into underground rock deposits

CO_2 sequestration is a potential method in basalt or basaltic-andesite for mitigating climate change reducing emission of greenhouse, which involve the injection of dissolved CO_2 deep into the underground formations that are rich in magnesium and calcium (Schwartz, 2022). Since basalts are huge in quantity around the world (most seabed and continents are composed of about 5% of basaltic rocks) have high content of ferromagnetic silicate and pore structure favoring good condition for CO_2 sequestration. Basically basalt consist of minerals, plagioclase (anorthite-albite, $CaAl_2Si_2O_8$-$NaAlSi_3O_8$) and pyroxene ($[Ca,Mg,Fe]2Si_2O_6$) as well as Olivine (Blondes et al., 2019). According to an estimate, about 3.5% or 5.6×10^6 km^2 of land on earth surface is occupied by sub volcanic or Basalt volcanic rocks. About 0.3 Gt tons of CO_2 are sequestered each year by mineral carbonation. This process bypasses the slower stage of conventional CO_2 storage (Gill & Fitton, 2022),(Brady & Gíslason, 1997). The relative abundance of CO_2 is high as compared to other greenhouse gases, hence it is more responsible for 64% increase in greenhouse effect (Sandalow et al., 2021). The super-critical CO_2 at pressure of 7.38 MPa and 31.1°C reacts with the calcium and magnesium to form stable carbonate minerals. This process permanently locks away the CO_2 and prevents it from escaping into the atmosphere due to rapid mineralization, which is actually the mimic of natural weathering of rocks with atmospheric CO_2 for mineralization with the difference is that this process is faster than the natural process of mineralization (Li & Hitch, 2017),26]. Huge amounts of basalt formation are found around the world especially in the BRI partner countries as shown in figure 4 that provides good opportunity for sequestration of CO_2 thereby potential global carbon cycle as these minerals contain bulk amount of magnesium and calcium ions that chemically react with CO_2 and form dolomites, calcite and magnesite. Lava is the main source of igneous rocks containing oxides, silicates, carbonates and sulphides. Igneous rocks that are formed during the cooling of lava are divided into plutonic or intrusive (solidification of lave inside earth surface) and volcanic or extrusive (solidification of lava above earth surface). Igneous rocks are divided into four categories based on the quantity of Silica (SiO_2): mafic (Basalt), ultramafic, felsic and intermediate (Miandad et al., 2012).

McGrail et al. performed an experiment at 50°C and 103 bars of PCO_2 in which they suspended hand sample basaltic rock into the supercritical CO_2. They notices the formation of secondary carbonate on the basalt within 95 days (McGrail et al., 2017). However, solubility of CO_2 in water cab be substantial that is at 300 bars and 100°C water solubility is about 2 mol% (Schaef & McGrail, 2009). Afterward Schaef et al. reacted basalt at 103 bars and 100°C in a static autoclaves and noticed a changing is occurring in weathering in one year time period that ranges from minor to severe (Saffar et al., 2020). During reaction of CO_2 solution with Basalt nearly all the CO_2 is absorbed at all temperatures ranging from 50 to 200°C and 300 bar but maximum extent as well as reaction rate occurs at 300 bar and 100°C (Bachu, 2000).. The recent famous basalt CO_2 sequestration project is at Iceland's Hellisheiði Geothermal Power Station by CarbFix since 2012, where hot water is drawn from the ground into the geothermal power station to dissolve CO_2 into the waste water and then injected hundreds of feet's deep into the basalt rocks (Cartier, n.d.). This project team found that about 90% of injected CO_2 is converted into mineral within a period of 2 years after injection.

A similar mineralization project is also working in flood basalts of Colombia River, United State. The future version of project CarbFix has been sponsored by the European Union to reduce geothermal emission by carbon capturing and sequestration, CCS. Since then many other projects are under progress in Australia, India, South Africa and Canada for the sequestration of CO_2 into the huge basaltic reserves in their countries (Balch et al., 2022). By including such CO_2 sequestration plants and projects und BRI initiative the possible environmental crisis due to transport and infrastructure can be mitigated (Raza et al., 2022).

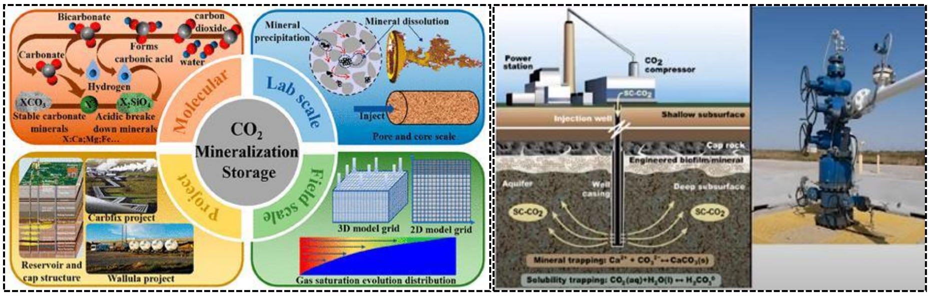


Figure 5: Overview of CO_2 injection into rock formation

Proposed ex-situ CO_2 sequestration technology for BRI framework

Another proposed potential mineral carbonation technique is ex-situ carbon capture of utilization, and storage (CCUS) that is set to become the primary approach for addressing carbon emissions in key industries (Yadav & Mehra, 2021). Ex-situ mineral carbonation involves the chemical transformation of CO_2 into stable mineral carbonates outside of the natural geological setting, using industrial processes (Sanna et al., 2014). This method utilizes minerals rich in calcium and magnesium, such as those found in ultrabasic rocks, to form carbonates that permanently sequester CO_2. Given the BRI's scale and its potential environmental impact, integrating ex-situ mineral carbonation into the initiative's framework could significantly contribute to reducing the carbon footprint of infrastructure projects. Moreover, this will also add value to industrial by-products, promoting sustainable development. Among the various CCUS methods, the ex-situ CO_2 mineralization storage approach has attracted much interest because of its benefits, such as abundant raw materials, wide distribution, environmentally friendly carbonate products, and the ability to achieve permanent storage without monitoring. However, the slow reaction speed of this CO_2 mineralization storage technology and the high cost of accelerated carbonation have affected its industrialization process (Sturmer et al., 2019). To reduce costs, measures include direct sequestration of CO_2 from flue gases, eliminating the CO_2 capture step; using calcium and magnesium-based waste as CO_2 mineralization raw materials to reduce raw material costs and detoxify waste; and increasing the application value of carbonation products to increase economic benefits (Sturmer et al., 2020). The authors' research on "mechanical activation of ultrabasic tailings-direct wet carbonation technology" reduced the net lifecycle cost of CCUS to 720 yuan/ton CO_2, but the utilization issue of carbonation products remains unresolved. Calcium and magnesium-based minerals have ex-situ carbonation solidification characteristics, which can be pressed, formed, and cured to increase their strength and produce carbonation materials with carbonate as the binding phase. Carbonation curing technology offers features such as a short process, simple operation, low cost, clean environment, and excellent material properties, enabling ex-situ CCUS technology to have broad application prospects in various fields (DiGiovanni et al., 2024).

Currently, there are several industrial applications of magnesium oxide cement, magnesium hydroxide stone, hydrated lime, low calcium cement, ordinary Portland cement, and solid waste containing cement clinker, such as steel slag, fly ash, blast furnace slag, and others (Aziz et al., 2020; T.-L. Chen et al., 2020; Du et al., 2022; Ho et al., 2017; Li, Zhao, et al., 2022; Luo & He, 2021; Mashifana & Sithole, 2021; Shu & Sasaki, 2022; X. Wang et al., 2019; YAN et al., 2016; Y. Zhang et al., 2019). However, these raw materials are typically available in small scales and may not meet the requirements for CO_2 mineralization storage for large-scale concentrated emission sources. Fortunately, ultrabasic mine tailings, including nickel, diamond, platinum group elements, and asbestos mines, contain a significant amount of magnesium silicate minerals needed for ex-situ CO_2 mineralization storage technology (Assima et al., 2014)(Mashifana & Sithole, 2021). The annual production of ultrabasic tailings worldwide is 1.5 times the global annual CO_2 emissions, and China's ultrabasic mines can store a total of $13.02\times10^{\wedge 12}$t CO_2, which is equivalent to 1887 times China's total emissions in 2008. Studies have shown that the carbonation solidification ability of serpentine in ultrabasic rocks is comparable to that of MgO cement, indicating the potential of serpentine to replace MgO cement as a carbonation cementitious material. However, there are limited reports on the carbonation solidification process using ultrabasic rocks as raw materials (Xu et al., 2023). The lack of understanding of the mechanism of carbonation solidification characteristics of ultrabasic tailings has hindered the design of ex-situ carbonation solidification processes for ultrabasic tailings, affecting the development and application of tailings carbonation materials, and limiting the research and development of new processes such as tailings carbonation solidification stacking and carbonation filling disposal. It is also essential to consider the solidification mechanisms of magnesium-based mineral carbonation. This process, which was initially proposed by Vandeperre and Al-Tabbaa in 2007, has since been the subject of extensive research (Vandeperre & Al-Tabbaa, 2007). The combined efforts of multinational research teams have improved our knowledge of the carbonation solidification properties of MgO cement and $Mg(OH)_2$, as well as their activation processes.

This technique of ex situ mineral carbonation will not only support the green BRI development, but it will also open new avenues of circular economy by converting the CO_2 emission into useful commercial products. Thus, this technique is more in line with BRI goals. Furthermore, the ex situ mineral carbonation technique also have the potential to utilize industrial waste like fly ash, steel slag, slag, desulphurized gypsum, waste concrete and other wastes from demolished building ensuring recycling and reuse phenomenon. This technique can valorize the waste materials from industry and rocks during the development of BRI infrastructure ensuring sustainable development.

For the successful adoption of these mineral carbonation techniques (in situ and ex situ) within the BRI framework this novel roadmap is proposed. However, there is a dire need of further investigation to find eligible BRI projects to acquire the necessary industrial wastes, agreements with business communities and development of scalable carbonation plants. This roadmap will further investigate the economic constraints and technological implications to ensure cost-effective mineral carbonation consistent with BRI objectives. For this we can seek the guidance of already functional mineral carbonation plants in different parts of the world (McGrail et al., 2017; Snæbjörnsdóttir et al., 2020). By implementing these novel techniques BRI can showcase its global commitment of sustainable development and combat climate change. This proactive technology not only solve urgent environmental issues but will also help in lowering global greenhouse gases. The creation of this roadmap will be a vital step toward achieving mineral carbonation's promise as a feasible CO_2 collection option throughout the BRI's vast network.

Scope

The scope of this roadmap is broadly categorized into the following four domains:

Domain # 1: Identification, 2D mapping, 3D modeling, quality and quantity estimation of rocks, minerals and tailing occurrences possessing a mineral carbonation potential.

Domain # 2: Material characterization and investigation for accelerated mineral carbonation of mafic and ultramafic rocks and tailings.

Domain # 3: Suitability studies of producing and utilizing stable carbonate compounds generated from mineral carbonation for industrial, commercial and household purposes. Some of the potential utilizations are;

a) Construction materials (aggregates, binders to replace cement)

b) Soil amendments for improving soil quality

c) Industrial applications (e.g., fillers in paints and plastics)

d) Potential for CO_2 sequestration through long-term carbon storage in landfills

e) Mining application (Mine backfilling materials after mineral carbonation)

This area increases the economic value of the mineral carbonation process by developing beneficial uses for the produced carbonates, supporting their broader adoption within BRI.

Domain # 4: To devise and initiate an awareness and environmental governance plan for mineral carbonation to address the climate change challenges.

Methodology for BRI framework mineral carbonation R &D

The following strategies will be adopted in this proposed R &D roadmap to achieve the suggested goals within BRI framework:

1) Fieldwork and Investigations (Domain #1: Identification and Resource Assessment)

1.1 Identifying Potential Sites:

Identifying the potential sites with outcrop exposures of Mafic and Ultramafic rocks using Multispectral and Hyper-spectral satellite and drone imagery and field observations and

1.2 Geological and topographical survey

Employ UAV (unmanned aerial vehicles) technology to conduct detailed

Geological and topographic surveys of identified potential regions.

- This data will be crucial for creating accurate maps and models (Domain #2).

2) Laboratory Work and Experimentation (Domains #2 & #3):

2.1 Data Processing and Modeling (Domain #1 & #2):

- Utilize photogrammetry, remote sensing, and GIS software to process field survey data, satellite imagery, and drone data.
- Generate detailed topographic maps, geological maps, and digital elevation models (DEMs) and surface models (DSMs) for the identified regions. These will inform resource assessment and project planning (Domain #1).

2.2 Material Characterization and Reaction Optimization (Domain #2):

- Characterize the mineralogical composition, reactivity, and surface properties of collected mafic and ultramafic rock samples and potential waste streams.
- Investigate methods to accelerate ex-situ mineral carbonation reaction rates (Domain #2) through innovative pre-treatment techniques (e.g., mechanical activation, chemical modification) (Objective 2).

2.3 Valorization of Stable Carbonates (Domain #3):

- Analyze the properties of the stable carbonate compounds produced from the mineral carbonation process (Objective 1).
- Conduct studies to assess their suitability for various applications, such as construction materials, soil amendments, or industrial fillers (Objective 1).
- Investigate the potential for utilizing mineral carbonation at household and industrial levels (Objective 1).

3) Desktop Studies (Domains #1, #3 & #4):

3.1 Mineral Resource Assessment (Domain #1, Supporting Objective 1):

- Employ geostatistical and simulation techniques to estimate the quality and quantity of potential ultramafic mineral resources within the identified regions.
- This information is essential for evaluating resource feasibility and project scale within the BRI framework (Domain #1).

3.2 Economic Modeling and Business Case (Domain #3):

- Develop economic models for various mineral carbonation use cases relevant to BRI countries, considering factors like capital costs, operational expenses, and potential revenue streams.
- Conduct sensitivity analysis and simulations to assess the economic viability of different scenarios.

3.3 Environmental Governance Framework and Policy Development (Domain #4):

- Conduct a comprehensive literature review and survey of existing global and national environmental governance laws relevant to mineral carbonation projects within China and Pakistan (BRI member states).

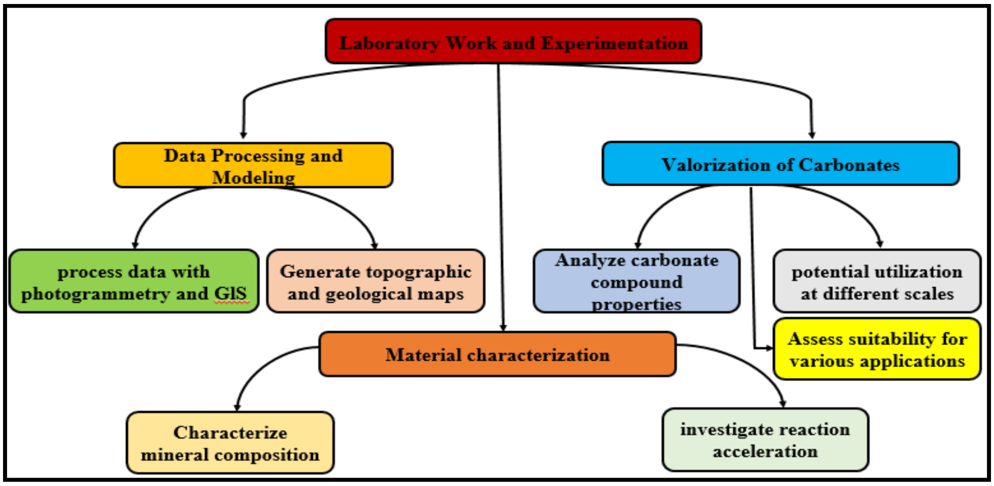
- Develop a framework that ensures responsible resource extraction, minimizes environmental impact, and fosters community engagement throughout the project lifecycle (Domain #4).

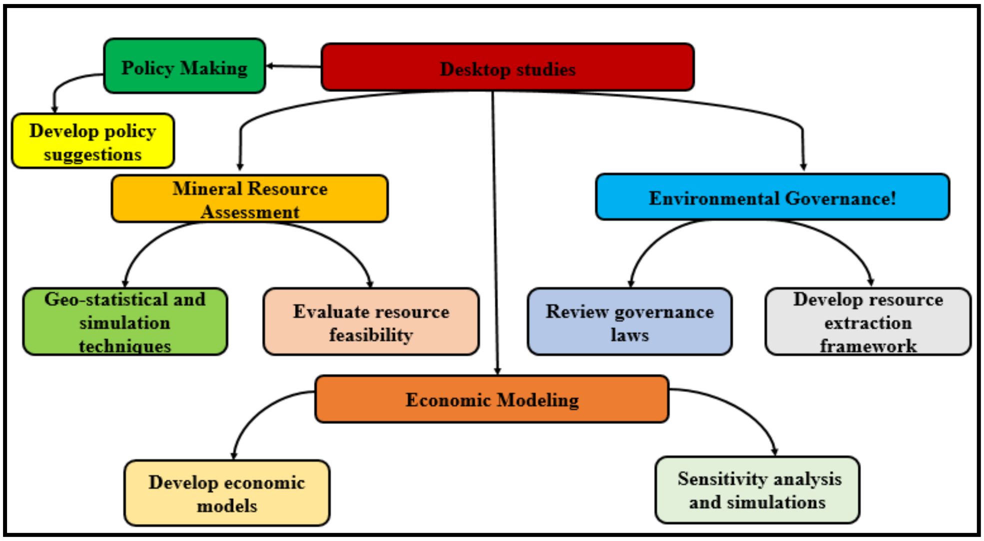
3.4 Policy Making (Domain #4):

- Based on the findings of the research, developing a suite of rules and recommendations for trade authorizations, offset credit verifications, and embedded emissions sequestration

4) Stakeholder Engagement:

- Throughout the project phases, engage key stakeholders, including industry representatives, research institutions, and national and international academics, to ensure successful knowledge sharing and implementation of the proposed roadmap.





This methodology aligns with research activity within the specific BRI domain it supports and addresses the objectives outlined in the proposal. By embracing a comprehensive approach integrating fieldwork, laboratory experiments, desktop studies, and stakeholder engagement, this R&D project has the potential to significantly advance the adoption of mineral carbonation as a climate change mitigation strategy within the BRI framework.

A flowchart of proposed methodology for topographic and geological mapping using satellite and drone is presented in figure 6.

Satellite image scenes will be acquired and analyzed by Geoinformatics software ENVI and SNAP to produce multiple useful image layers that can help in geological mapping in multiple mapping sheets on 1:50,000 scale. Geological mapping can be carried out by using multiple image layers created as color composites and band ratios as fellow.

a) Differentiation of different geologies/lithologies,

b) Structural alignments and features,

c) Alteration, surface characteristics, vegetation cover, land/water, and healthier greenery

d) Shaded relief, outcrops and drainage networks.

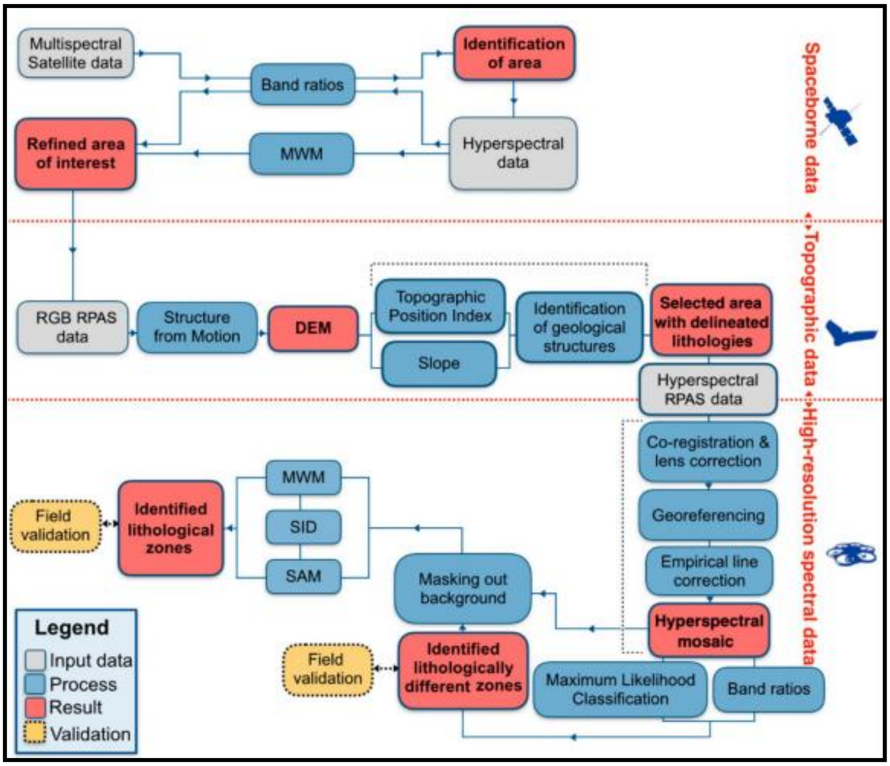


Figure 6; Flowchart of Using Satellite Multispectral, Hyperspectral Imaging and drones for geological and topographic mapping (Booysen et al., 2019)

Sample geological maps generated using hyper-spectral satellite imagery is shown in Figure 6 and 7. Figure 6 shows a Sentinel-2 Principal Component Analyses (PCA) and hydrothermal altered basement outcrop covered by sand sheets on left side. The dyke swarm (black lines) crossing the basement (pink) buried in Ordovician sediments (green and dark brown) are also highlighted on the said map on right side. Figure 7 shows a lithological composite image. This type of imaging is useful for differentiating various types of surface cover types and general geology. It also displays alkalic granitoids in blue, granitic gneiss in yellow, and hydrothermally altered granite rich in muscovite clay in orange-red tones. The way of working of aerial topographic survey using drones already carried out by research is presented in Figure 8.

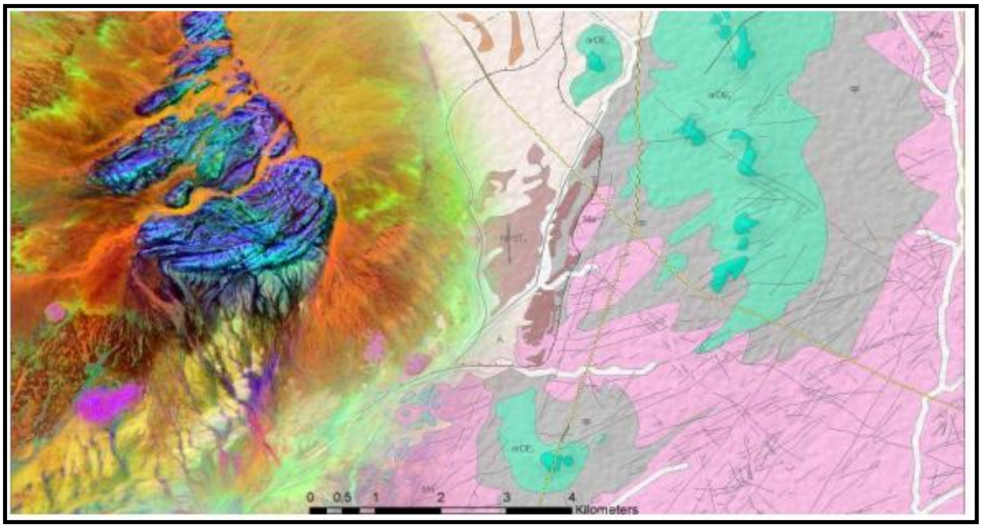


Figure 7: Geological map generated using Sentinal-2 satellite imagery (Courtesy: GAF AG)

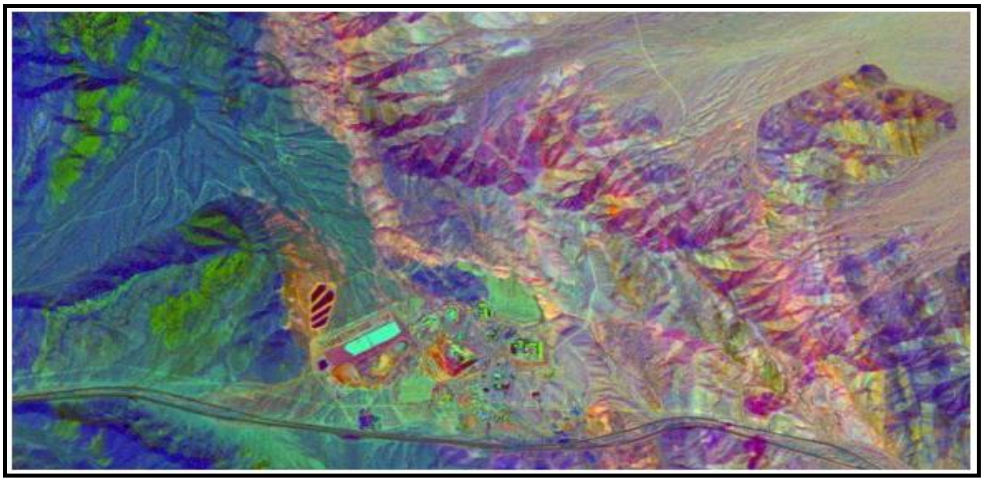


Figure 7; Lithological color composite image

Figure 8; Ways of working of aerial topographic survey

Conclusion

Key outcomes upon successful completion of this proposed R & D roadmap are:

(1) Detailed topographic and geological maps, quality and quantity estimation of mineral resources suitable for ex-situ and in-situ mineral carbonation within identified regions of BRI countries as well as assessment of the CO_2 storage capacity of potential geological formations for geological sequestration.

(2) Identification of optimal reaction parameters (e.g., temperature, pressure, pre-treatment methods) to accelerate and enhance the efficiency of ex-situ mineral carbonation processes.

(3) Development of cost-effective ex-situ mineral carbonation technologies suitable for large-scale adoption within diverse BRI economies.

(4) Comprehensive characterization of the physical and chemical properties of stable carbonate compounds produced from ex-situ mineral carbonation processes.

(5) Utilization of stable compounds produced from mineral carbonation at an industrial and commercial level.

(6) Establishment of a comprehensive environmental governance framework for responsible and sustainable implementation of mineral carbonation projects across BRI countries, addressing potential environmental and social impacts.

(7) Development of policy recommendations for effective regulation and support of mineral carbonation technologies within the BRI framework

(8) Public awareness and policy recommendations for environmental governance relating mineral carbonation geological sequestration.

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