Heliyon 10 (2024) e25419

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Carbon capture, utilization and storage opportunities to mitigate greenhouse gases

Muhammad Imran Rashid [a], Zahida Yaqoob [b], M.A. Mujtaba [c], M.A. Kalam [d], H. Fayaz [e,*], Atika Qazi [f]

[a] Chemical, Polymer and Composite Materials Engineering Department, University of Engineering and Technology, Lahore (New Campus), 39021, Pakistan
[b] Department of Material Science and Engineering, Institute of Space Technology, Islamabad, 44000, Pakistan
[c] Department of Mechanical Engineering, UET Lahore (New Campus), Lahore 54890, Pakistan
[d] School of Civil and Environmental Engineering, FEIT University of Technology Sydney, NSW 2007, Australia
[e] Modeling Evolutionary Algorithms Simulation and Artificial Intelligence, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[f] Centre for Lifelong Learning, Universiti Brunei Darussalam, Brunei Darussalam

ARTICLE INFO

Keywords:
CCUS opportunities
Climate change induced flooding
CO_2 mitigation technologies
Mineral carbonation
Shiger serpentinite belt

ABSTRACT

Carbon capture, utilization and storage (CCUS) technologies are utmost need of the modern era. CCUS technologies adoption is compulsory to keep global warming below 1.5 °C. Mineral carbonation (MC) is considered one of the safest and most viable methods to sequester anthropogenic carbon dioxide (CO_2). MC is an exothermic reaction and occur naturally in the subsurface because of fluid-rock interactions with serpentinite. In serpentine carbonation, CO_2 reacts with magnesium to produce carbonates. This article covers CO_2 mitigation technologies especially mineral carbonation, mineral carbonation by natural and industrial materials, mineral carbonation feedstock availability in Pakistan, detailed characterization of serpentine from Skardu serpentinite belt, geo sequestration, oceanic sequestration, CO_2 to urea and CO_2 to methanol and other chemicals. Advantages, disadvantages, and suitability of these technologies is discussed. These technologies are utmost necessary for Pakistan as recent climate change induced flooding devastated one third of Pakistan affecting millions of families. Hence, Pakistan must store CO_2 through various CCUS technologies.

1. Introduction

Pakistan is facing potential risk to the economy, social and environmental development due to the extreme impacts of climate change highlighted by United Nations Framework Convention on Climate Change (UNFCCC) [1,2]. Climate change badly affected Pakistan and Himalayan glaciers are melting faster [3]. Rains, floods and earthquakes occur more frequently [4]. Emissions of greenhouse gases (GHGs) in the atmosphere are constantly increasing with ever-growing energy needs and population. Climate change and global warming are main concerns in 21st century. GHGs especially CO_2 is released into the atmosphere due to world energy dependence on fossil fuels. Many industries are responsible for GHGs emissions such as cement industry emits 5 % GHGs [5,6]. In the coming century, it's not possible to absorb these GHGs and CO_2 concluded by global carbon cycle, so adaptation technologies to

* Corresponding author.
E-mail address: fayaz@tdtu.edu.vn (H. Fayaz).

https://doi.org/10.1016/j.heliyon.2024.e25419
Received 5 October 2023; Received in revised form 15 January 2024; Accepted 25 January 2024
Available online 1 February 2024
2405-8440/

capture CO_2 are required urgently [7–10].

Paris agreement was a legal binding which is signed in 2015 by 166 countries including Pakistan.

The aim of Paris Agreement was to reduce the GHGs emission to address the issue of global warming as the temperature of earth is higher than the pre-industrial period. Paris agreement does not focus only on the reduction of GHGs emissions but also focus on the management of forests, better use of land and the availability of financial and technical resources for underdeveloped countries to combat the negative impact of climate change especially global warming. It signaled the lower dependence on fossil fuels for membered countries [11]. Global warming must be kept below 1.5 °C as per IPCC recommendations [12].

The intergovernmental panel on climate change (IPCC) directs CO_2 storage and utilization for the mitigation of greenhouse gas concentrations [13]. Carbon dioxide capture and storage refer to the necessary technologies in the immediate future, aiming to store the CO_2 produced from the combustion of fossils fuels in steel and iron making, cement manufacture [14] and power generation and then store it underground into stable geological sites for a very long time [7,15,16]. There are many approaches to sequester CO_2 such as mineral carbonation, geological sequestration, oceanic sequestration, biological sequestration [17–19]. Pakistan has a greater potential and availability of natural minerals, which can be utilized to capture CO_2 through mineral carbonation. Similarly, vast deposits of serpentine exist in the northern region of Pakistan [20]. This study is based on a survey in Pakistan highlighting feedstock minerals availability in Pakistan, detailed characterization of serpentine, its potential utilization for greenhouse gases mitigation and different ways of CO_2 sequestration. Process of carbon mineralization involve the dissolution of magnesium silicates such as serpentine and olivine with successive precipitation of carbonates and silica [21].

2. Background and CO_2 mitigation techniques implementation requirement

Prolonged monsoon rains due to climate change affected one third of Pakistan population (Fig. 1). Fig. 1 shows damaged houses per district in different areas throughout Pakistan [22]. Millions of people were affected, and estimated loss is more than 30 billion US dollars (According to Asian Development Bank). Similar climate change induced flooding is also observed in India and China.

Climate change can be mitigated through CO_2 utilization and storage. Ten pathways [23] for CO_2 utilization and storage are given in Fig. 2. Various techniques can be used for carbon capture, utilization and storage [24]. These CO_2 mitigation techniques are chemical production, oceanic storage, geological storage, mineralization and many more (Fig. 2).

Mission Innovation report (2018) has introduced the concept of enhanced metal recovery (EMR) and mineral carbonation is used for recovery of valuable metals along with CO_2 sequestration [25]. Three potential EMR routes exist, in-situ, ex situ EMR as a heap leaching process and ex situ EMR in a dedicated processing plant [26]. Wang et al. recovered 90 % of nickel and cobalt through EMR and convert magnesium into magnesite in an integrated process which used natural olivine [27]. Nickel and cobalt are used in electric vehicles, battery storage, hydrogen production and fuel cells [28]. Through conventional froth flotation process, 30 % of the nickel may waste as mine tailings which is due to nickel locked inside silicate grains. Mineral carbonation especiallay pH swing process may

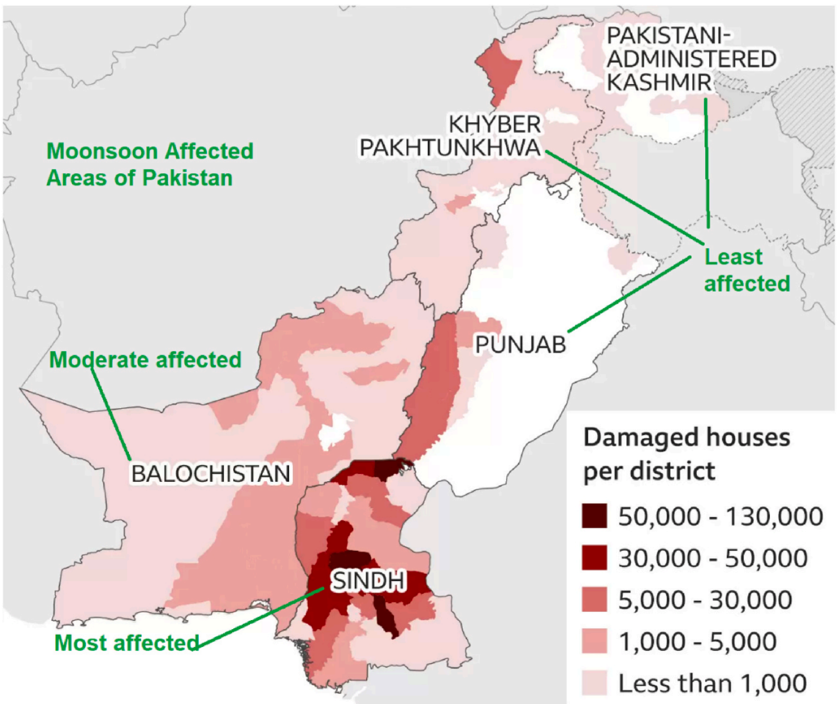

Fig. 1. Climate change affected one third of pakistan population [22].

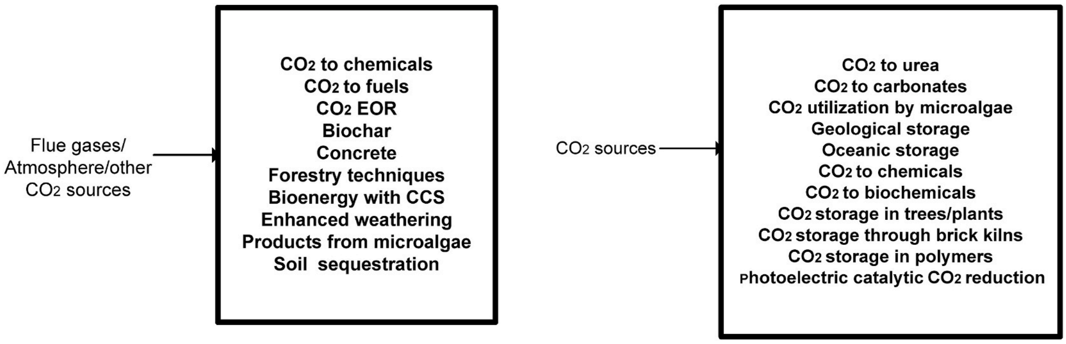

Fig. 2. Ten pathways for carbon capture (left), CO_2 mitigation techniques (right).

use these mine tailings and recover this nickel along with CO_2 sequestration [28]. Wang et al. reacted CO_2 with saprolite and limonite laterites and olivine and carbonate Mg^{+2} present in them while nickel and cobalt were leached in aqueous solution using nitrilotriacetic sodium which were recovered through sulphide precipitation [29].

2.1. Mineral carbonation

CO_2 is separated from flue gases using different membranes. Aqueous mineral carbonation can be used to transform this separated CO_2 into carbonates with different rocks (dunite) and minerals (Olivine, Antigorite, and Lizardite) using CO_2 separation membranes and its fixation may provide significant contributions in CO_2 mitigation [30]. Mineral carbonation is a mature technology and permanent CO_2 storage. Single stage carbonation [31–36], two stage carbonation [37–39] and acid dissolution [40–42] are all currently being investigated. The by-products and minerals feed can also be used in cement production [40]. Direct carbonation is better than indirect carbonation. Mineral carbonation is a leading technology as it is a permanent storage and can be employed at any place especially in vicinity of CO_2 emissions.

2.2. CO_2 to urea

It is best method to store CO_2 permanently on large scale. In this method CO_2 reacts with ammonia to form carbamate which decompose into urea that is used by plants [43,44]. Urea is used as a fertilizer for crops and CO_2 fixed through this process is at large scale and cannot return. This process is normally employed in fertilizer sector where CO_2 is a byproduct of ammonia production process. CO_2 from other CO_2 emitting industries such as cement industry and steel manufacturing may be coupled with fertilizer industries to convert it into urea fertilizer as fertilizer production is dependent on CO_2 availability.

2.3. Utilization of CO_2 in microalgae

CO_2 is eaten by microalgae. Numerous microalgae growth characteristics have been observed to increase with rising CO_2 concentrations [45]. The biomass created by microalgae can once more be used in the combustion process. Microalgae perform better than terrestrial plants [46]. A bioprocess can transform the hemicellulose of plants into compounds. Using microalgae impregnation, biodiesel can be made from ethanol [47]. Microalgae plantation can be increased artificially to enhance CO_2 storage. This can be coupled with biodiesel production from microalgae.

2.4. Enhanced oil recovery

Although it is not a permanent storage, CO_2 is employed in enhanced oil recovery. Although it is momentarily confined, there is a potential of leakage. Excess CO_2 from gas treatment facilities may be used in fertilizer industries to manufacture urea. Pakistan has significant potential for enhanced oil recovery as it has gas and oil wells for these fuels' exploration. Major issue in this technology is to ship CO_2 from emitting facilities to the enhanced oil recovery sites. Although this is a temporary CO_2 fixation but still it contributes in immediate CO_2 mitigation.

2.5. Geological CO_2 storage

There is no doubt that CO_2 is kept in geological storage [48–50], but leaks are possible. However, its significance for the immediate reduction of CO_2 emissions cannot be disputed. It is necessary to determine risks and potential uses for escaping CO_2. Thousands of people were killed by CO_2 that released after an African lake exploded [51].

2.6. CO_2 to chemicals

It is the method of permanent storage of CO_2 and it can be converted into ethylene carbonate, urea and salicylic acid [52]. CO_2 is fixed permanently in the form of chemicals.

2.7. CO_2 to biochemicals

Different biochemicals like carbon monoxide, methane, glucose, methanol, and synthetic fuel can be produced. Enzymes are necessary for CO_2 fixation, and it is a slow process. Further research on discovering new enzymes that accelerate CO_2 fixation is required.

2.8. Storage of CO_2 in trees and plants

Plants use CO_2 during the process of photosynthesis. It is quick and permanent process of storing CO_2. There is a dire need to increase the number of trees and plants worldwide to capture the excessive amount of CO_2. Millions of trees has been planted in Pakistan through Billion Tree Tsunami program.

2.9. CO_2 capture through brick kilns

Major emissions from brick kilns are CO_2 and particles which affect environment [53]. Scrubbers using amines can capture these emissions. Such techniques must be adopted worldwide to mitigate greenhouse gas emissions. Coupling amines systems with brick kilns can significantly reduce CO_2 emissions and particulate matter. Such measures will offset CO_2 emissions.

2.10. Storage of CO_2 in polymers

Polymerization reaction consume CO_2. Different polymers can store CO_2 by using adsorption and absorption process [54,55]. Binding CO_2 in polymers will enhance CO_2 fixation.

2.11. Oceanic CO_2 storage

It is quite risky because it may cause damage to marine life. There are large number of ocean available worldwide for this process. Pakistan also has oceans which can be used for CO_2 sequestration. Oceanic CO_2 storage is temporary but can be utilized to offset current CO_2 emissions and delay global warming process.

2.12. CO_2 reduction using photoelectric catalysts

This is an emerged technology which has a potential to sequester huge mass of anthropogenic CO_2 emissions [56,57]. Further

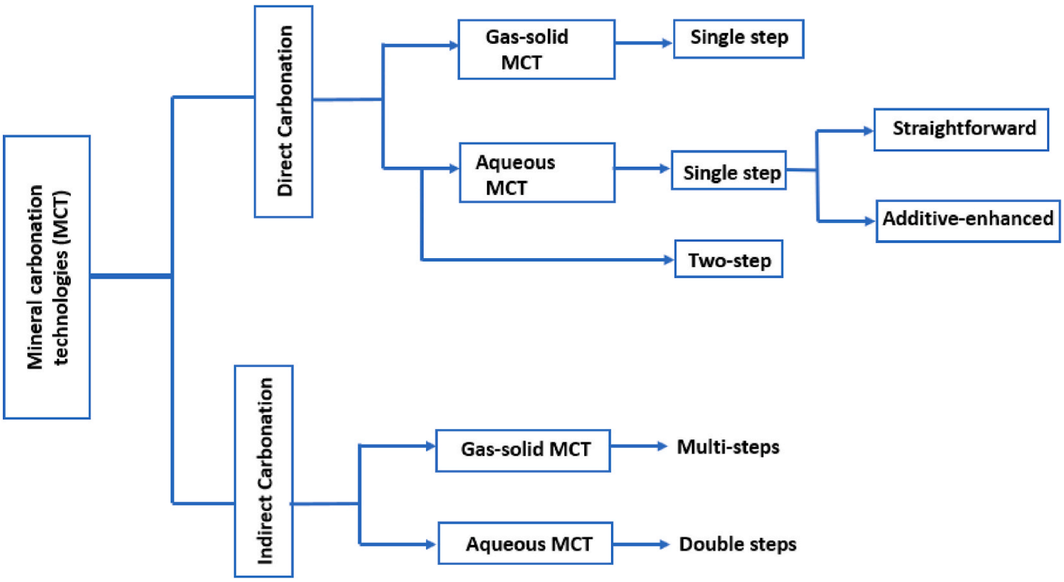

Fig. 3. Mineral carbonation processes for CO_2 sequestration [64].

research is required to develop efficient photoelectric catalysts.

3. Mineral carbonation by natural and industrial materials

Mineral carbonation (proposed in 1990s) is an alternate of silicates weathering [58]. CO_2 mineral storage or mineral carbonation permanently fix anthropogenic CO_2 without having chances of leakage [59]. Ex-situ mineral carbonation and in-situ mineral carbonation are widely used. Mineral carbonation converts CO_2 into magnesite ($MgCO_3$), calcite ($CaCO_3$) or dolomite [60]. Magnesium and calcium silicates are used worldwide for this process. Similarly, Pakistan has considerable resources of magnesium and calcium silicate rocks, which can be utilized for potential CO_2 storage and capture [20,61]. Magnesium silicates are peridotite (olivine, forsterite) and serpentinite (lizardite, antigorite, chrysotile). These materials may bind all emitted CO_2 from fossil fuels [62,63]. Mineral carbonation processes are shown in Fig. 3.

4. Mineral carbonation feedstock availability in Pakistan

Potential feedstock minerals such as serpentine (lizardite and antigorite) and olivine are widely found in ophiolite belt [63]. The northern region of Pakistan (Fig. 4) have large amounts of these materials. Serpentine is deposited at highest position of the Skardu. Pakistan is quarried from a mountain range around 4000 m above sea level which is 38 km from Shiger (Fig. 5) and it posses Serpentine stone. Serpentine belt is shown in Fig. 5 (a) and serpentine mineral is shown in Fig. 5 (b). Moreover, very high quality olivine exits in Pleo-Island Arc (North Pakistan) [65]. Mineral carbonation technology can be implemented in these areas of Pakistan resulting in CO_2 mitigation. Other option is to transport these mineral and rocks where CO_2 emissions exist and store them via reaction with these minerals and rocks.

X-ray diffraction analysis (Fig. 6) show that serpentinites consist of lizardite, clinochlore, and talc. The most abundant minerals are polymorphs of serpentine (lizardite, d = 7.5938 Å; clinochlore d = 4.767 Å; talc = 3. 11 Å).

FTIR techniques (Fig. 7) is used to investigate the adsorption of water from atmospheric air, the hydroxyl groups (-OH) in the spectral region of 3675 cm^{-1}. Si–O symmetrical stretching vibration silicate range at 871-1050 cm^{-1} [66].

SEM and EDS analysis of serpentine powder is shown in Fig. 8. SEM disclose typical serpentine structure. Layered structure of serpentine is visible in SEM images [Fig. 8 (a,b)]. Fig. 8 (c) shows area selected for EDS analysis. EDS analysis (Fig. 8 (d)) indicate Mg, Si, O, Ca, Al and W elements are present. These elements are typical for serpentine.

5. CCUS opportunities in Pakistan and their suitability

5.1. Geo sequestration and availability of depleted gas and oil reservoirs

Conventional storage sites for geologic storage include CO_2 storage in underground geological cavities such as depleted gas, oil

Fig. 4. Geological map of serpentine and olivine formation in Pakistan.

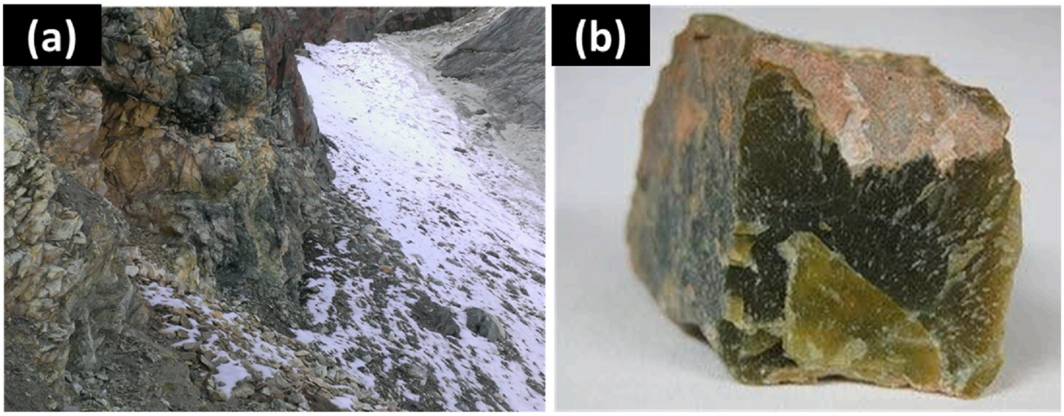

Fig. 5. Serpentinite belt is a metamorphic rock in Shiger Skardu Pakistan composed of serpentine group minerals (lizardite, talc, and clinochlore) (a) serpentine belt (b) serpentine mineral.

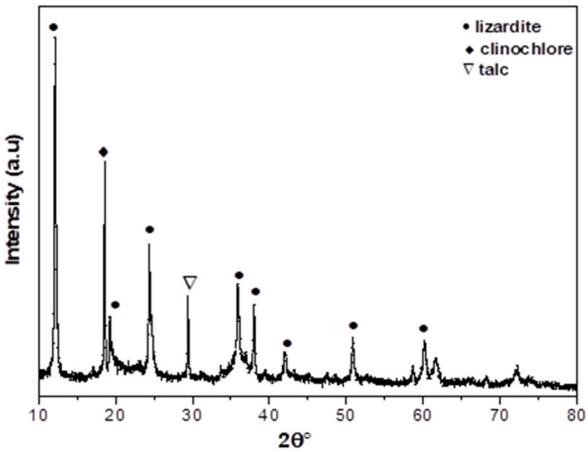

Fig. 6. XRD pattern of Serpentinite rock from Shiger Skardu Pakistan.

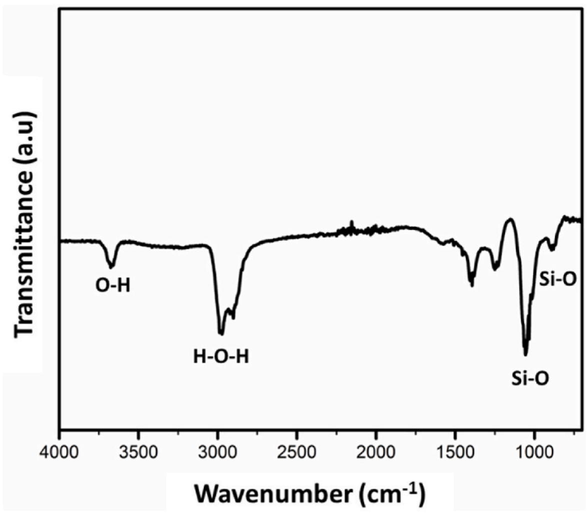

Fig. 7. FTIIR spectrum of Serpentine rock from Shiger Skardu Pakistan.

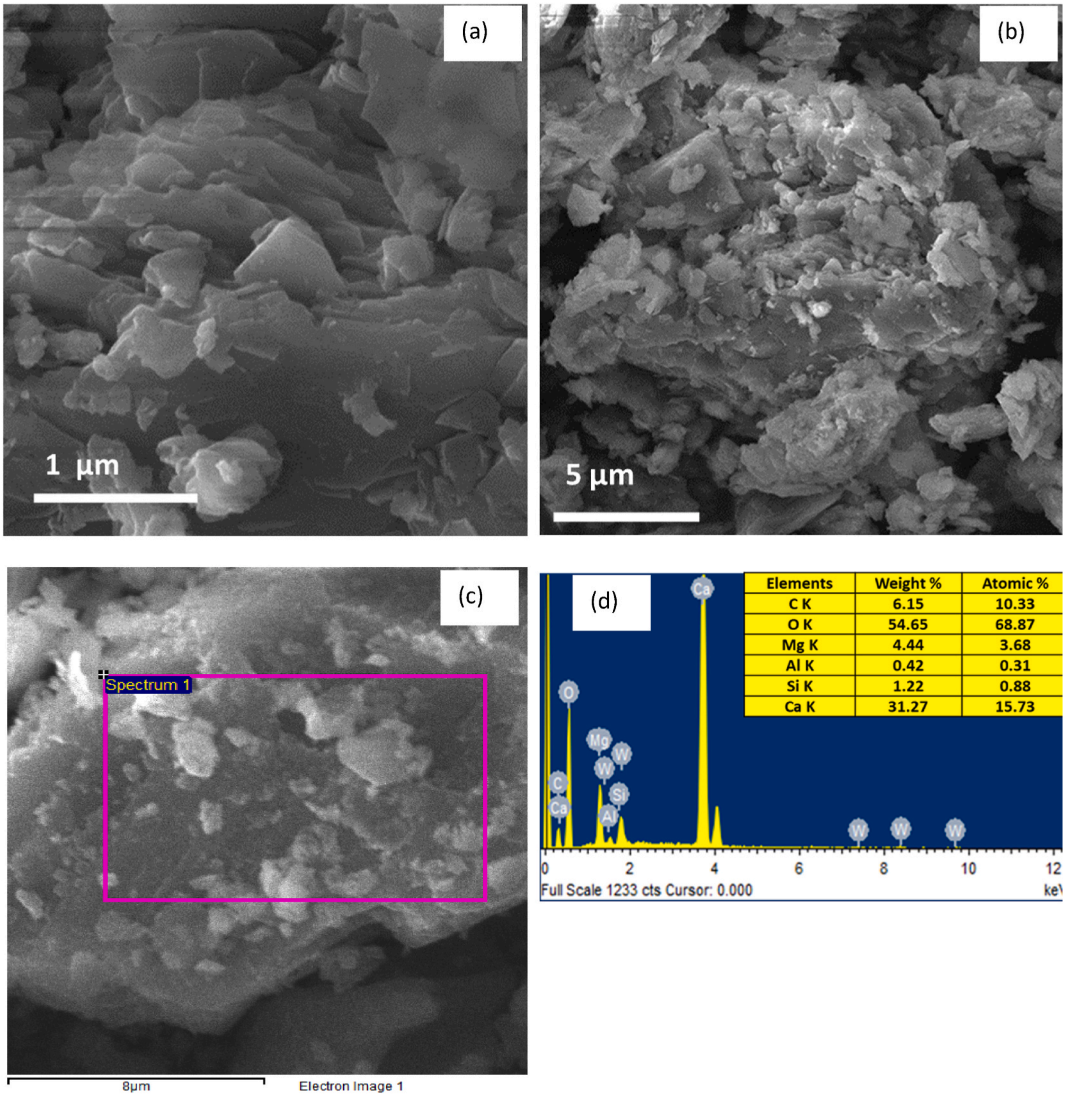

Fig. 8. SEM at different magnification and EDS analysis of powdered serpentine from Shiger Skardu Pakistan (a) serpentine particles (b) zoom in view of serpentine particles (c) area on serpentine particle for EDS analysis (d) EDS analysis of serpentine particle.

reservoirs, saline aquifers, salt caverns and coal seams. Initially, the CO_2 is transported to a storage site after separation from a flue gas offshore emitting source which is finally injected into an underground reservoir at high pressure. However, the potential concern with geological storage is the hazard of leakage which require constant monitoring over long term [67,68]. Pakistan has various depleted reservoirs having potential for CO_2 storage. This technology is a suitable option for Sindh and Balochistan where plenty of depleted gas and oil reservoirs exist. Main limitation of the technology is releasing potential of stored CO_2.

5.2. *Oceanic sequestration*

Our planet contributes the largest carbon sinks in the oceans [13]. As ocean storage can be used for injecting CO_2 into the ocean at a broad depth of around 1500 m [68], where carbonic acid is formed [69]. However, the challenge with this method of storage is decreasing pH and lack of permanency which can cause environmental endangerment having adverse impacts on marine life. The storage below the seabed is another form of CO_2 sequestration, where CO_2 is pumped at deeper depth into the sea [70]. At such depths, it eliminates monitoring requirement because CO_2 become denser than water offering greater permanency of storage [68]. Pakistan has oceans which can be used for CO_2 storage. This technology is suitable for Sindh especially Karachi city where oceans exist in close vicinity. Main limitations of the technology are availability of oceans and release potential of stored CO_2.

5.3. CO_2 for urea production

CO_2 can be converted into urea via reaction with ammonia typically in a fertilizer industry. These reactions are shown in equation 1 and equation 2. This reaction occurs at high pressure (3200 psig) and temperature (383 F) with excess ammonia (4.5/1). Excess ammonia is recovered through ammonia recovery condensers and recycled back to reactor.

$CO_2 + 2NH_3 = NH_4COONH_2$ (1)

$NH_4COOHNH_2 = NH_2CONH_2 + H_2O$ (2)

(Ammonium carbamate)→(Urea) + (Water).
Overall reaction

$CO_2 + 2NH_3 \rightarrow NH_2CONH_2 + H_2O$

Various fertilizer industries exist in Pakistan which transforms CO_2 into urea and have capacity typically 1750 metric tonne per year (MTD) to 2000 MTD. List of fertilizer industries in Pakistan is given in Table 1. This technology is suitable for Punjab as oceanic sequestration and geo sequestration does not suit for Punjab. Main benefit of the technology is conversion of huge amount of CO_2 into urea. Main limitation of urea manufacturing technology is availability of natural gas.

5.4. CO_2 for methanol and other chemicals production

Methanol is one of the most promising chemicals as well as clean burning fuel. Moreover, it is also useful for obtaining acetic acid, dimethyl ether, methyl tertiary butyl ether, and methylamine [71]. Industrially, large amount of methanol can be produced from the catalytic conversion of synthesis gas such as CO_2, CO, and H_2 [72]. Other chemicals which can be produced from CO_2 are ethylene carbonate, salicylic acid, formaldehyde, formic acid, di-methyl carbonate, copolymers, cyclic carbonates, polymer building blocks and fine chemicals [52]. Pakistan can use flue gases from recently installed coal power plants or other industries and produce methanol through process shown in Fig. 9. Methanol production can also be used to fullfil domestic methanol requirements. This technology is suitable for Punjab because most of the CO_2 emitting industries such as cement industries and steel industries are in Punjab. These CO_2 emissions can be converted into methanol.

5.5. Direct air capture technology

Direct air capture (DAC) is another emerging technology for CO_2 capture. CO_2 concentration in air has reached 419 ppm due to anthropogenic CO_2 emissions into atmosphere [34]. DAC process enables CO_2 capture from atmosphere thus helping in circular economy. According to IEA in a sustainable development scenario, 10 Gt CO_2 emissions must be captured by 2070. From 10 Gt emissions, it is expected that 2 Gt emissions will be captured through DAC technology. Ninety percent of these emissions must be stored underground and 10 % be converted into CO_2 based fuels. In DAC process, absorbents capture CO_2 from air flow using these absorbents. Chemical sorbents are hydroxides of sodium, potassium and calcium and CaO. These hydroxides and oxides bind CO_2 from air. These absorbents can be regenerated through heating. Currently 27 CCUS facilities are capturing 40 Mt CO_2 emissions [73]. DAC is a mature technology which Pakistan can adopt to capture CO_2 emissions and offset climate change affects. This technology is suitable for all provinces of Pakistan and can be installed at any place.

6. Conclusions and recommendations

CO_2 mitigation technologies especially mineral carbonation can be employed in Pakistan to offset greenhouse gases in Pakistan and reduce global warming which can reduce devastating flooding caused by monsoon. Based on characterization analysis, calcium oxide and iron oxide have a higher sequestration capacity. The presence of lizardite, talc, and clinochlore were confirmed by XRD analysis in serpentine from Shiger serpentine belt. Therefore, this study has shown that MC can be used in Pakistan for CO_2 sequestration. To line

Table 1
Urea manufacturing fertilizer industries in Pakistan and their capacity.

Urea fertilizer industry	Capacity (Metric tonne per day)	Location
FatimaFert Sheikhupura	1750	Sheikhupura
FFC Sadiqabad plant 1	2105	Sadiqabad
FFC Sadiqabad plant 2	1925	Sadiqabad
FFC Mirpur Mathelo plant 3	1740	Mirpur Mathelo
Engro Dharki plant 1	3500	Dharki
Engro Dharki plant 2	2740	Dharki
FFBL Karachi	1670	Karachi
Fatima fertilizer Sadiqabad	3500	Sadiqabad
PakAmerican Mianwali	1050	Mianwali
PakArab fertilizer Multan	300	Multan

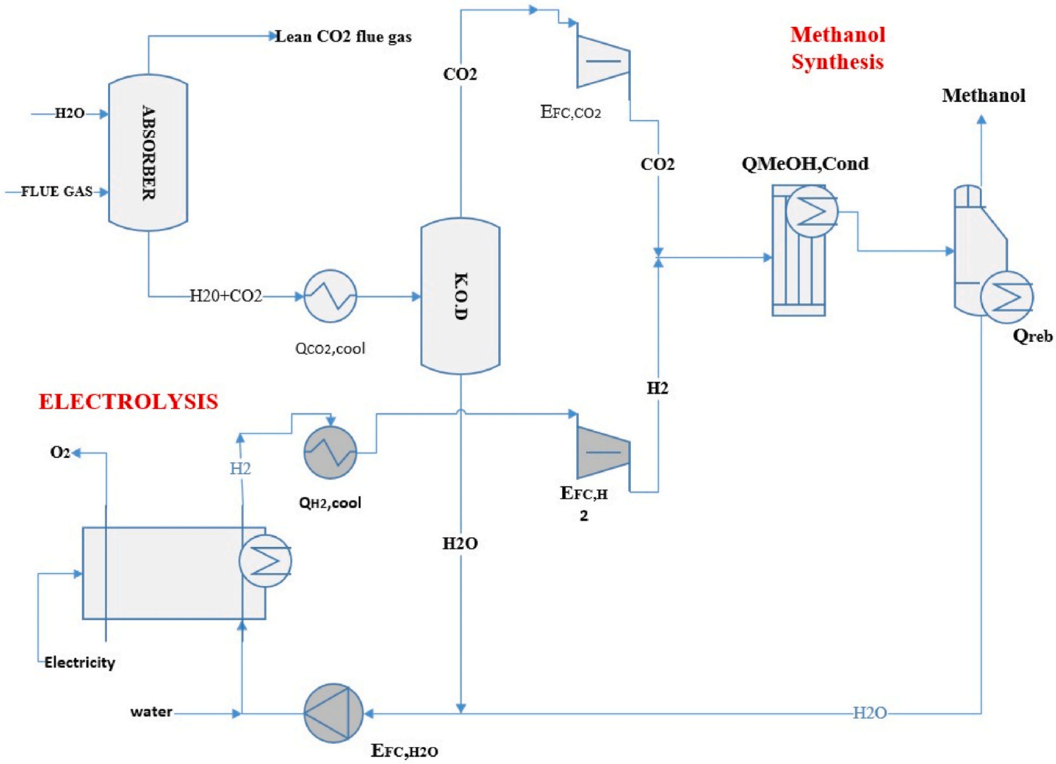

Fig. 9. Methanol production from flue gases.

with the concept of green technology, Pakistan has an indigenous serpentine reserve of Shiger serpentine belt which can be used for environmental sustainability in climate mitigation strategies. Furthermore, CO_2 can be converted into urea, methanol and other chemicals. Depleted oil and gas reserves available in Pakistan can be utilized for enhanced oil recovery. Oceanic CO_2 storage and direct air capture are also viable option which can be used in Pakistan. Coupling amines systems with brick kilns, microalgae plantation, trees plantation and increasing urea and methanol production facilities can also offset CO_2 emissions thus reducing greenhouse gases and monsoon caused flooding.

Data availability statement

Data will be provided on demand.

CRediT authorship contribution statement

Muhammad Imran Rashid: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Zahida Yaqoob:** Writing – review & editing, Data curation. **M.A. Mujtaba:** Writing – review & editing, Software, Resources. **M.A. Kalam:** Writing – review & editing. **H. Fayaz:** Writing – review & editing, Funding acquisition. **Atika Qazi:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work is supported by Universiti Brunei Darussalam under research grant UBD/RSCH/URC/RG(b)/2020/023.

References

[1] M.A. Khan, et al., The challenge of climate change and policy response in Pakistan, Environ. Earth Sci. 75 (5) (2016) 1–16.
[2] A.N. Salik, COP21 Paris, Strategic Studies 37 (2) (2017) 74–89.
[3] N. Abas, et al., Review of GHG emissions in Pakistan compared to SAARC countries, Renew. Sustain. Energy Rev. 80 (2017) 990–1016.

[4] National Climate Change Policy. Government of Pakistan, 2012.
[5] E.R. Bobicki, et al., Carbon capture and storage using alkaline industrial wastes, Prog. Energy Combust. Sci. 38 (2) (2012) 302–320.
[6] A. Azdarpour, et al., CO2 sequestration using red gypsum via pH-swing process: effect of carbonation temperature and NH4HCO3 on the process efficiency, Int. J. Miner. Process. 169 (2017) 27–34.
[7] A. Sanna, et al., A review of mineral carbonation technologies to sequester CO 2, Chem. Soc. Rev. 43 (23) (2014) 8049–8080.
[8] O. Rahmani, An experimental study of accelerated mineral carbonation of industrial waste red gypsum for CO2 sequestration, J. CO2 Util. 35 (2020) 265–271.
[9] W. Liu, et al., CO2 mineral carbonation using industrial solid wastes: a review of recent developments, Chem. Eng. J. 416 (2021) 129093.
[10] O. Rahmani, A. Kadkhodaie, J. Highfield, Kinetics analysis of CO2 mineral carbonation using byproduct red gypsum, Energy Fuel. 30 (9) (2016) 7460–7464.
[11] Hunter, D., International Environmental Law - American Bar Association. 2021..
[12] C.C. School, State of the Planet, 2021. Available from: https://news.climate.columbia.edu/2021/12/16/net-zero-pledges-can-they-get-us-where-we-need-togo/#:~:text=To%20avoid%20the%20catastrophic%20impacts,reach%20net%20zero%20by%202050.
[13] B. Metz, O. Davidson, H. De Coninck, Carbon Dioxide Capture and Storage: Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2005.
[14] E. Benhelal, E. Shamsaei, M.I. Rashid, Challenges against CO2 abatement strategies in cement industry: a review, J. Environ. Sci. 104 (2021) 84–101.
[15] F. Li, et al., Global projections of future wilderness decline under multiple IPCC Special Report on Emissions Scenarios, Resour. Conserv. Recycl. 177 (2022) 105983.
[16] M.F. Qureshi, et al., CO2 hydrate stability in oceanic sediments under brine conditions, Energy 256 (2022) 124625.
[17] M.E. Boot-Handford, et al., Carbon capture and storage update, Energy Environ. Sci. 7 (1) (2014) 130–189.
[18] J. Li, A.D. Jacobs, M. Hitch, Direct aqueous carbonation on olivine at a CO2 partial pressure of 6.5 MPa, Energy 173 (2019) 902–910.
[19] M.Z. Kashim, et al., Reaction mechanism of wollastonite in situ mineral carbonation for CO2 sequestration: effects of saline conditions, temperature, and pressure, ACS Omega 5 (45) (2020) 28942–28954.
[20] M.I. Rashid, E. Benhelal, S. Rafiq, Reduction of greenhouse gas emissions from gas, oil, and coal power plants in Pakistan by carbon capture and storage (CCS): a review, Chem. Eng. Technol. 43 (11) (2020) 2140–2148.
[21] V. Romanov, et al., Mineralization of carbon dioxide: a literature review, ChemBioEng Rev. 2 (4) (2015) 231–256.
[22] Bbc, Pakistan floods, Map and Satellite Photos Show Extent of Devastation, 2022.
[23] C. Hepburn, et al., The technological and economic prospects for CO2 utilization and removal, Nature 575 (7781) (2019) 87–97.
[24] M.I. Rashid, Truth and Flase-Carbon Dioxide Mitigation Technologies, Non-Metallic Material Science, 2021.
[25] F. Bourgeois, CO2 Use, Meeting the Dual Challenge A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage, National Petroleum Council, Washington, 2019, 2019.
[26] N. etal, Mission Innovation, Accelerating the Clean Energy Revolution: Carbon Capture Innovation Challenge: Report of the Carbon Capture, Utilization, and Storage Experts' Workshop, 2017.
[27] F. Wang, D. Dreisinger, Carbon mineralization with concurrent critical metal recovery from olivine, Proc. Natl. Acad. Sci. USA 119 (32) (2022) e2203937119.
[28] S. Wilson, J.L. Hamilton, Fizzy ore processing sequesters CO_2 while supplying critical metals, Proc. Natl. Acad. Sci. USA 119 (39) (2022) e2212424119.
[29] F. Wang, D. Dreisinger, An integrated process of CO2 mineralization and selective nickel and cobalt recovery from olivine and laterites, Chem. Eng. J. 451 (2023) 139002.
[30] O. Rahmani, et al., Experimental investigation and simplistic geochemical modeling of CO2 mineral carbonation using the mount tawai peridotite, Molecules 21 (3) (2016) 353.
[31] M.I. Rashid, Mineral Carbonation of CO2 Using Alternative Feedstocks, The University of Newcastle, Australia, 2019.
[32] M.I. Rashid, et al., Development of Concurrent grinding for application in aqueous mineral carbonation, J. Clean. Prod. 212 (2019) 151–161.
[33] M.I. Rashid, et al., ACEME: direct aqueous mineral carbonation of dunite rock, Environ. Prog. Sustain. Energy 38 (3) (2019) e13075.
[34] M.I. Rashid, Testing and validating instruments for feedstocks of mineral carbonation, Mineralogy (2021) 1–27. IntechOpen.
[35] M.I. Rashid, et al., Application of concurrent grinding in direct aqueous carbonation of magnesium silicates, J. CO2 Util. 48 (2021) 101516.
[36] M.I. Rashid, et al., Aqueous carbonation of peridotites for carbon utilisation: a critical review, Environ. Sci. Pollut. Control Ser. 29 (50) (2022) 75161–75183.
[37] E. Benhelal, et al., "ACEME": synthesis and characterization of reactive silica residues from two stage mineral carbonation Process, Environ. Prog. Sustain. Energy 38 (3) (2019) e13066.
[38] Benhelal Emad, M. Hook. James, Rashid Muhammad Imran, Zhao Guangyu, Tim Oliver, Mark Rayson, Brent Geoff, Michael Stockenhuber, Kennedy Eric, Insights into chemical stability of Mg-silicates and silica in aqueous systems using 25 Mg and 29Si solid-state MAS NMR spectroscopy: applications for CO2 capture and utilisation, utilisation, Chem. Eng. J. 420 (2020) 127656.
[39] M.I. Rashid, et al., Application of a concurrent grinding technique for two-stage aqueous mineral carbonation, J. CO2 Util. 42 (2020) 101347.
[40] E. Benhelal, et al., The utilisation of feed and byproducts of mineral carbonation processes as pozzolanic cement replacements, J. Clean. Prod. 186 (2018) 499–513.
[41] E. Benhelal, et al., Study on mineral carbonation of heat activated lizardite at pilot and laboratory scale, J. CO2 Util. 26 (2018) 230–238.
[42] M.I.B. Rashid, E, F. Farhang, M. Stockenhuber, E.M. Kennedy, Magnesium leachability of Mg-silicate peridotites: the effect on magnesite yield of a mineral carbonation process, Minerals 10 (2020) 1091.
[43] N.R. Muhammad Imran Rashid, Urea Synthesis Hazard Analysis–PHA, HAZOP and Quantitative Risk Assessment, LAMBERT Academic Publishing AG & Co. KG, Dudweiler Landstraße 9966123 Saarbrucken, Germany, 2012, 100.
[44] M.I. Rashid, N.R, Fluid mechanics and heat-transfer operations combination involved in urea unit of fertilizer complex, Non-Metallic Material Science 1 (1) (2019) 5–10.
[45] E. Aghaalipour, A. Akbulut, G. Güllü, Carbon dioxide capture with microalgae species in continuous gas-supplied closed cultivation systems, Biochem. Eng. J. 163 (2020) 107741.
[46] D. Tang, et al., CO2 biofixation and fatty acid composition of Scenedesmus obliquus and Chlorella pyrenoidosa in response to different CO2 levels, Bioresour. Technol. 102 (3) (2011) 3071–3076.
[47] A. Jafari, et al., New insights to direct conversion of wet microalgae impregnated with ethanol to biodiesel exploiting extraction with supercritical carbon dioxide, Fuel 285 (2021) 119199.
[48] J. Gale, Geological storage of CO2: what's known, where are the GAPS and what more needs to be done, in: J. Gale, Y. Kaya (Eds.), Greenhouse Gas Control Technologies - 6th International Conference, Pergamon, Oxford, 2003, pp. 207–212.
[49] G. Shaffer, Long-term effectiveness and consequences of carbon dioxide sequestration, Nat. Geosci. 3 (7) (2010) 464–467.
[50] A. Sanna, et al., A review of mineral carbonation technologies to sequester CO2, Chem. Soc. Rev. 43 (2014) 8049–8080.
[51] K.S. Lackner, Carbonate chemistry for sequestering fossil carbon, Annu. Rev. Energy Environ. 27 (2002) 193–232.
[52] E. Alper, O. Yuksel Orhan, CO2 utilization: developments in conversion processes, Petroleum 3 (1) (2017) 109–126.
[53] K. Achakzai, et al., Air pollution tolerance index of plants around brick kilns in Rawalpindi, Pakistan, J. Environ. Manag. 190 (2017) 252–258.
[54] A. Sattari, et al., The application of polymer containing materials in CO2 capturing via absorption and adsorption methods, J. CO2 Util. 48 (2021) 101526.
[55] H. Safaa, A.S.H. Mohamed, Emad Yousif, Mohammad Hayal Alotaibi, D.S.A.a.G.A. El-Hiti, New porous silicon-containing organic polymers:synthesis and carbon dioxide uptake, Processes 8 (2020).
[56] Z. Ni, et al., Research progress of electrochemical CO2 reduction for copper-based catalysts to multicarbon products, Coord. Chem. Rev. 441 (2021) 213983.
[57] C. Xu, et al., Accelerating photoelectric CO2 conversion with a photothermal wavelength-dependent plasmonic local field, Appl. Catal. B Environ. 298 (2021) 120533.
[58] W. Seifritz, CO2 disposal by means of silicates, Nature 345 (6275) (1990) 486.
[59] K.S. Lackner, A guide to CO2 sequestration, Science 300 (5626) (2003) 1677–1678.

[60] B. Metz, O. Davidson, H.C. Coninck, M. Loos, L.A. Meyer (Eds.), Special Report on Carbon Dioxide Capture and Storage, 2005.
[61] S. Holloway, et al., An assessment of the CO2 storage potential of the Indian subcontinent, Energy Proc. 1 (1) (2009) 2607–2613.
[62] K. Lackner, H. Ziock, From low to no emissions, Mod. Power Syst. 20 (2000).
[63] A.A. Olajire, A review of mineral carbonation technology in sequestration of CO2, J. Petrol. Sci. Eng. 109 (2013) 364–392.
[64] M. Werner, S. Hariharan, M. Mazzotti, Flue gas CO 2 mineralization using thermally activated serpentine: from single-to double-step carbonation, Phys. Chem. Chem. Phys. 16 (45) (2014) 24978–24993.
[65] P. Bouilhol, et al., Gem olivine and calcite mineralization precipitated from subduction-derived fluids in the Kohistan arc-mantle (Pakistan), Can. Mineral. 50 (5) (2012) 1291–1304.
[66] W. Abdelwahab, et al., Production of spinel forsterite refractories using sheared serpentinized ultramafic rocks, UM Seleimat, Egypt, ARPN J. Eng. Appl. Sci. 14 (2019) 3386–3400.
[67] R. Saran, V. Arora, S. Yadav, CO2 sequestration by mineral carbonation: a review, Glob. Nest J 20 (2018) 497–503.
[68] D. Voormeij, G. Simandl, Geological, ocean, and mineral CO2 sequestration options: a technical review, Geosci. Can. 31 (1) (2004) 11–22.
[69] O. Izgec, et al., CO2 injection into saline carbonate aquifer formations I, Transport Porous Media 72 (1) (2008) 1–24.
[70] P.G. Brewer, et al., Experiments on the ocean sequestration of fossil fuel CO2: pH measurements and hydrate formation, Mar. Chem. 72 (2–4) (2000) 83–93.
[71] F. Dalena, et al., Methanol production and applications: an overview, Methanol (2018) 3–28.
[72] É.S. Van-Dal, C. Bouallou, Design and simulation of a methanol production plant from CO2 hydrogenation, J. Clean. Prod. 57 (2013) 38–45.
[73] P. Madejski, et al., Methods and techniques for CO2 capture: review of potential solutions and applications in modern energy technologies, Energies 15 (3) (2022) 887.