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Carbon dioxide (CO_2) Emissions Mitigation in the Context of Geological Carbon Sequestration

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Abstract

Climate change has serious negative implications on environments and human health. Carbon dioxide (CO_2) emissions majorly from power plant is considered as a major pollutant contributing to the problem of climate change. Hence, carbon capture and sequestration (CCS) technique has been identified as a mitigation option to reduce this emission. This review gives a clear picture of CO_2 sequestration technology and explore recent improvements in research and developments of CCS. The mitigation approach and several modes of CO_2 storage are presented in this work. The sequestration techniques that have covered in this review are storage in geological formations such as deep saline aquifers, oil and gas reservoirs, deep coal seams, and basalts. Each of these techniques has its strengths and weaknesses which have also been discussed. Oceanic sequestration which can provide the largest possible sink for CO_2 if it is thermodynamically stable and safe, is also explained along with other types of geological CO_2 storage. Finally, some of the examples of storage projects worldwide are explored. CO_2 storage in the Sleipner, Weyburn and In Salah projects indicate that it is realistic to store CO_2 in geological formations as a CO_2 mitigation option.

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Introduction

The major contributor to the problem of climate change that is threatening the world is CO_2 emission majorly from power plant. The CO_2 causes outrageous heating of the earth's atmosphere and, therefore, contributes to the global warming (Abidoye *et al.*, 2015; Rabiu *et al.*, 2017). Carbon capture and sequestration (CCS) is considered as one of the most promising techniques available to reduce atmospheric CO_2 emissions (Abidoye *et al.*, 2015; Bachu, 2008; Bachu, 2000; Rabiu *et al.*, 2020; Song and Zhang, 2013). However, safety of long-term storage remains necessary and further investigations are required from scientific researchers (Alcalde *et al.*, 2018; Bachu, 2008; Bachu, 2000; Bergmann *et al.*, 2010; Caesary *et al.*, 2020; De Silva *et al.*, 2015; Druckenmiller and Maroto-Valer, 2005; Khudaida and Das, 2014; Lee *et al.*, 2020; Pan *et al.*, 2020; Rathnaweera *et al.*, 2016; Song and Zhang, 2013; Song *et al.*, 2020).

It is paramount to understand that for CCS to be publicly accepted, it must be safe and securely stored underground for years without contaminate the atmosphere and groundwater. The monitoring of CO_2 in the sedimentary basins includes checking for CO_2 leakage at the surface or subsurface where groundwater are situated (Abidoye *et al.*, 2015; Rabiu *et al.*, 2020; Schmidt-Hattenberger *et al.*, 2013). At the surface, CO_2 is generally detected by equipment such as infrared detectors. In groundwater, the presence of CO_2 can be detected by tools such as pH and geoelectrical properties (Abidoye *et al.*, 2014; Ajayi *et al.*, 2019; Bachu, 2000; Bachu *et al.*, 2007; Kelemen *et al.*, 2019; Khudaida and Das, 2014).

The accomplishment of CCS technology aims at reducing the content of greenhouse gases such as CO_2 that is entering into the atmosphere (Dafflon *et al.*, 2013; Kelemen *et al.*, 2019; Kharaka *et al.*, 2010). The technique of CCS starts with the capturing of carbon dioxide and its associated compounds from producing sources such as power plant; the CO_2 is compressed and transport through pipelines and store underground for geological timescale (Abidoye *et al.*, 2015; Ajayi *et al.*, 2019; Khudaida and Das, 2014; Rabiu *et al.*, 2017). Some recent works explained the different physicochemical methods responsible for suitable CO_2 storage (Druckenmiller and Maroto-Valer, 2005; Gaasbeek *et al.*, 2014; Liu and Maroto-Valer, 2011; Rabiu *et al.*, 2020; Wei *et al.*, 2011). For example, Rabiu *et al*. (2020) study the effect of different factors (i.e., pH, temperature, salinity, and surfactant) on σ_b–S_w and ε_b–S_w relationships in porous rock media. The main motive of this review paper is to present the importance of CO_2 sequestration techniques. Also, some areas of CCS projects worldwide and their limitations are discussed. The injected CO_2 can be stored in the reservoir formations. CO_2 storage has been executed in various parts of the world like the USA, UK, Germany, and Australia. The storage can be divided into man-made and natural modes of storage. While man-made storage includes storage in geological formations such as saline aquifers and depleted oil and gas, natural modes include terrestrial sequestration. The principal aim of carbon geological sequestration is to make use of porous media with high porosity that can sufficiently accommodate CO_2; they must also have reasonably impermeable caprock or seal that can block the CO_2 leakages from escaping into the atmosphere. On one hand, majority of deep saline aquifers or other geological storage projects are storing CO_2 in a liquid or supercritical form. On the other hand, there may be opportunities for CO_2 to be stored by mineralisation and the technology is underway (Rabiu *et al.,* 2017). CO_2 mineralisation is very safe because it can convert the CO_2 into useful raw materials, but the process is very slow, and more research is required in this area.

Several Modes of CO_2 Storage

Terrestrial sequestration

This is the capturing of CO_2 from the atmosphere and storage in the vegetation and soil. It is the process of CO_2 removal from the atmosphere through photosynthesis.

Ocean Sequestration

Oceanic sequestration has been identified as the largest possible sink for carbon dioxide storage with an estimated potential storage of 40,000 gigatonnes (Gt) of CO_2. There is possibility that oceanic sequestration can store over 90% of current CO_2 emissions. CO_2 is injected into the water body at depths below 1 km either from moving ships or pipelines. At this depth, the density of water is lower than the injected CO_2 and the latter will be sink and dissolve into the water body (Metz *et al.,* 2005). However, there are concerns over the environmental implications of CO_2 on aquatic and marine life because the injection of liquid CO_2 into the deep ocean will change its chemistry and increase its acidity (Voormeij, 2004; Metz *et al.*, 2005). Although, ocean storage has the possibility of storing about 90% of all the CO_2 emission worldwide. Nevertheless, there is much discussion ongoing about its negative implications on the marine life. More research is required from scientific communities to fill the gap on the environmental implications of CO_2.

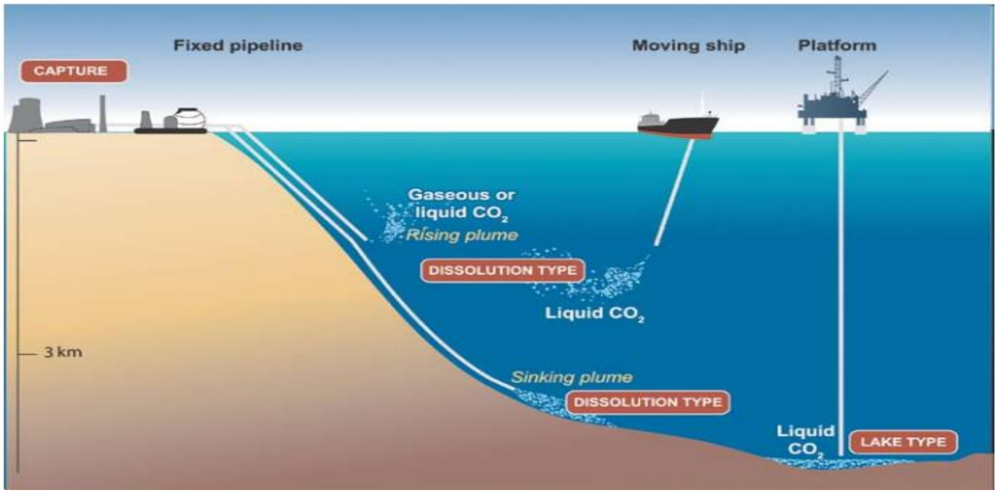

Figure 1: Oceanic storage methods (Metz *et al.,* 2005)

Geological Sequestration

This is the most popular CO_2 sequestration technology that is used worldwide. Under normal atmospheric conditions, CO_2 is a gas, and it is heavier than air. At a temperature greater than 31.1^{o}C and pressures greater than 74 bar (critical point), CO_2 is in a supercritical state and have the properties of both gases and liquid (Fig. 2).

The Suitability of CO_2 in Carbon Sequestration

CO_2 is described as a chemical compound that has two elements i.e., carbon and oxygen in the ratio of one to two. It can be noted that the physical state of CO_2 varies with pressure and temperature (Figure 2). For example, at very low temperatures and high pressure, CO_2 is a solid (i.e., hydrate formation). CO_2 is said to be in a supercritical state at temperature of 31.1^{O}C and pressure of 74 bar. At this state, CO_2 behaves as a gas but has a density of liquid. Figure 4 shows the variability of the density of CO_2 as a function of pressure and temperature (Solomon, 2006). All the above characteristics of CO_2 and other criteria are to put into consideration before choosing the appropriate methods and sites for CO_2 storage in geological formations. CO_2 can be stored in various phases, for example, it can be stored in gaseous, liquid and supercritical phase depending on temperature and pressure of the sedimentary basin (Bachu, 2000).

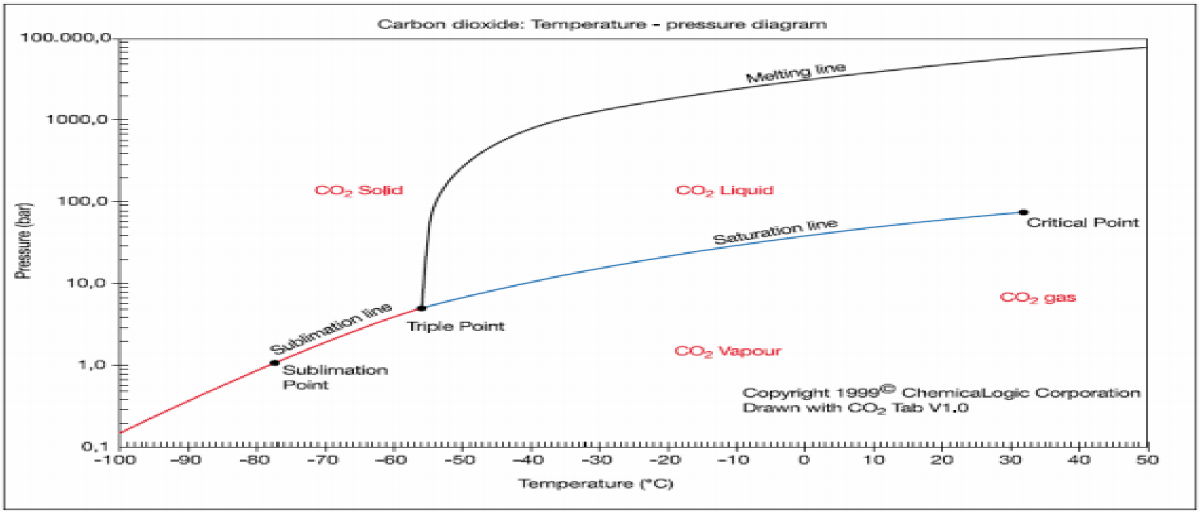

Figure 2 CO_2 Phase diagram(Solomon, 2006)

Geological formations such as saline aquifers, depleted oil and gas reservoirs, basalts, and un-mineable coal beds can be used as a storage medium for CO_2. Table 1 discussed the types of CO_2 geological formations.

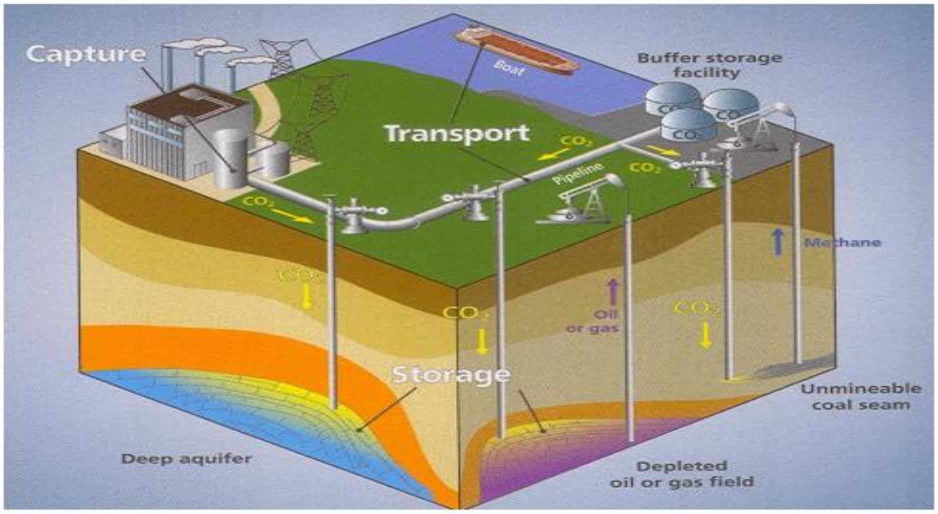

Figure 3: Carbon Capture and Sequestration Processes (Hartai, 2012)

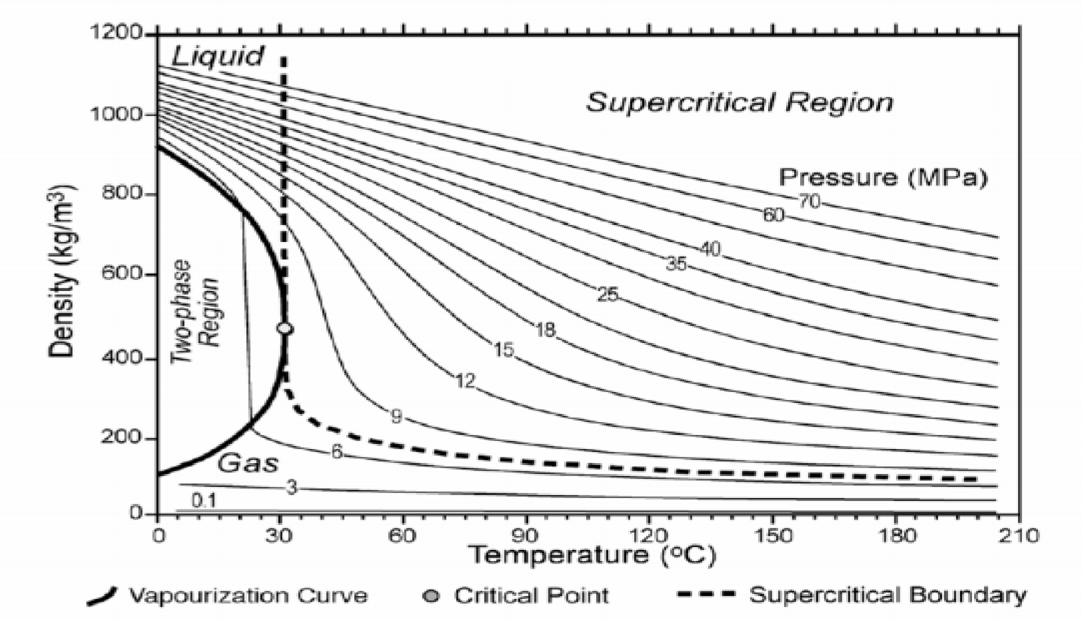

Figure 4 Variation of CO_2 density in connection with pressure and temperature (Solomon, 2006)

Table 1: Types of geological CO_2 storage (Hartai, 2012)

	CO_2 Capacity (Gt)	Advantages	Limitations
Saline Aquifers	400 – 10000	Saline aquifers are the best formations for CO2 storage because of their largest capacity and they are available worldwide. They can be used for irrigation purposes.	They are poorly characterised. They are generally far from CO_2 emission sites.
Depleted oil and gas	930	It is economical because it can be used for CO_2 storage and also for enhanced oil recovery. The sites have been previously characterised. Hence, due to their secure nature which have been able to retain oil and gas over a long period of time makes them suitable candidates.	They have limited capacities
Un-mineable coal seams	40	CO_2 is used for recovery of methane from coal seams during the enhanced coal bed methane recovery process. Produced methane from this source can be used as an energy source.	There are injection problems due to the poor permeability of the coal. They have limited capacities
Basalts	-	Basalt has some potential for CO_2 mineral trapping because injected CO_2 may interact with silicates in the basalt to form precipitate carbonate minerals (Metz *et al.*, 2005).	Basalt has low porosity and low permeability.

Examples of storage projects in the world: The selected global CO_2 storage projects are as follows:

CO_2 Storage Project in Sleipner, Norway using Saline Aquifer Formation

The injection of the CO_2 started since 1996 and it is the first commercial project. CO_2 is captured and separated from the natural gas and pumped down to the Utsira Formation. About 1Mt of CO_2 per year is pump into the formation and the estimate of 20Mt of the total CO_2 is stored over entire lifetime. The formation has an extensive and thick shale layer that serve as seal to prevent CO_2 from leakage (Hartai, 2012).

CO_2 Storage Project in In Salah, Algeria using Depleted Oil and Gas Reservoir

In Salah storage project is the first commercial scale CO_2 storage and started in 2004. It has 4 production and 3 injection wells. About 1 Mt CO_2 / year of CO_2 stored into the Krechba (sandstone) reservoir. The caprocks are made up of thick layer of mudstones (shales). The total estimation of CO_2 stored over entire lifetime is 17 Mt CO_2.

CO_2 storage Project in Weyburn, Canada using Depleted Oil and Gas Reservoir

The CO_2 injection started since 2000. The CO_2 source is a coal gasification company that is producing 95% pure CO_2. The seal consists of anhydrite and shale which prevent the leakage of CO_2. The estimate of total stored CO_2 over entire lifetime is 20 Mt CO_2 (Hartai, 2012)

RECOPOL Project, Poland: Un-Mineable Coal Seams

This is a European Union co-funded research and demonstration project. The injection and production started in 2004. Carbon dioxide is pumped in coal seam at a depth of 1000 metres. The project involve the simultaneous production of methane and storage of CO_2 (Hartai, 2012).

Monitoring Techniques

The major drawback of CCS is the leakage of CO_2 after the injection. Modelling and simulation studies have been conducted in the establishment, implementation, and monitoring phases of CO_2 storage. These processes are done primarily to avoid leakage of CO_2 gas into the atmosphere and groundwater aquifers. The CO_2 leakage could be as a result of faults and fractures, aquifer over-pressurisation and abandoned well (Ajayi *et al.*, 2019). Therefore, cost effective and reliable monitoring will boost the confidence of CCS technology. A brief summaries of subsurface monitoring techniques are discussed in the table 2.

Table 2 Subsurface Monitoring Methods

Monitoring method	Functions
Electromagnetic resistivity	Measurement of the electrical conductivity (EC) of the subsurface such as groundwater, soil.
Vertical seismic profile (VSP)	It can provide robust data on CO_2 concentration
Magnetotelluric sounding	It calculates the changes in electromagnetic field
Multi component 3-D Surface Seismic Time-lapse Survey	It can give high quality information on the CO_2 distribution and migration
Resistivity log	It is used for the characterisation of the fluids and rock
Aqueous Geochemistry	Chemical composition measurement in the storage basins
Gamma ray logging	It is used for the characterisation of rock and sediment in a borehole
Cross-well seismic survey	It is used for the subsurface characterisation
Electrical resistance tomography (ERT)	Monitoring CO_2 movement between the wells by using high resolution techniques

Simulation Tools

The CO_2 behaves in a specific way depending on certain conditions such as fluid characteristics, injection rates, trapping mechanism, and storage types. For the sequestration process to be safe, effective, and efficient, it is very vital to study and predict the behaviour of CO_2 to be injected at a specific site, guided by previously available data. Simulation tools can be used to predict the behaviour of the CO_2 during the injection and monitoring processes. They can also be used to predict the movement of CO_2 plume during and after injection process. Table 3 explains some of the applications of various simulation tools that have been explored in various studies.

Table 3 Various types of simulation tools used in various studies

Name of simulation tool	Application in CO_2 storage	Reference
STOMP, PFLOTRAN	Dispersion of model plume and interaction of CO_2 with reservoir fluids	(Khudaida and Das, 2014)
Eclipse, GEM-GHG, NUFT	CO_2 plume dispersion model	Ajayi *et al.*, 2019
TOUGH-FLAC	Modelling CO_2 plume dispersion and the impact of stress due to CO_2 interaction	Ajayi *et al.*, 2019
SIMED	Coal seam reservoir modelling	Ajayi *et al.*, 2019
PHREEQC	Model the effect of long-term mineral trapping and change in porosity due to the presence of CO_2	Ajayi *et al.*, 2019
COMSOL	Model the CO_2 movement	Ajayi *et al.*, 2019

CCS Technologies in Europe

Presently, there are about 78 commercial scale projects around Europe that are in various stages of development according to Scottish Carbon Capture and Storage (SCCS). Amongst, only three are in operation, 21 are in a pilot phase, and those in planning/speculative stage or in design are 18. The remaining 36 of these projects have been dormant/cancelled or completed. Most of these plants are hosted by the UK and followed by Norway, The Netherlands, and Germany (Kelemen *et al.*, 2019). Two (2) of the three plants that are in operation (Snohvit in Norway and Sleipner in Norway) utilise saline aquifers as their sequestration sites and the third one in The Netherlands uses depleted oil and gas formations (Kelemen *et al.*, 2019).

Conclusions

Carbon capture and sequestration technique is a crucial mitigation option for the problem of climate change. This work presents a review of state-of-the-art developments in CO_2 sequestration and discusses recent advances in research and developments for CO_2 storage. Oceanic sequestration can store majority of the CO_2 emissions because of its largest capacity; however, the technology is still immature, and more research is required in this area. And finally, other types of geological CO_2 storage and some of the examples of storage projects worldwide are explored.

References

Abidoye, L. K., Khudaida, K. J. and Das, D. B. (2015). Geological Carbon Sequestration in the Context of Two-Phase Flow in Porous Media: A Review. *Critical Reviews in Environmental Science and Technolgy :45*(11), 1105–1147. https://doi.org/10.1080/ 10643389.2014.924184

Ajayi, T., Gomes, J. S., and Bera, A. (2019). A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Petroleum Science*, *16*(5), 1028–1063. https://doi.org/10.1007/s12182-019-0340-8

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M.V , Ogaya, X., and Haszeldine, R. S. (2018). Estimating geological CO2 storage security to deliver on climate mitigation. *Nature Communications*, *9*(1), 2201. https://doi.org/10.1038/s41467-018-04423-1

Bachu, S. (2008). CO2 storage in geological media: Role, means, status and barriers to deployment. *Progress in Energy and Combustion Science*, *34*(2), 254–273. https://doi.org/10.1016/j.pecs.2007.10.001

Bachu, S. (2000). Sequestration of CO2 in geological media: Criteria and approach for site selection in response to climate change. *Energy Conversion*, 18.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N. P., and Mathiassen, O. M. (2007). CO2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, *1*(4), 430–443. https://doi.org/10.1016/S1750-5836(07)00086-2

Bergmann, P., Lengler, U., Schmidt-Hattenberger, C., Giese, R., and Norden, B. (2010). Modelling the geoelectric and seismic reservoir response caused by carbon dioxide injection based on multiphase flow simulation: Results from the CO2SINK project. *Geochemistry, 70,* 173–183. ttps://doi.org/10. 1016/j.chemer.2010.05.007

Caesary, D., Song, S. Y., Yu, H., Kim, B., and Nam, M. J. (2020). A review on CO2 leakage detection in shallow subsurface using geophysical surveys. *International Journal of Greenhouse Gas Control*, 20

Dafflon, B., Wu, Y., Hubbard, S. S., Birkholzer, J. T., Daley, T. M., Pugh, J. D., Peterson, J. E., and Trautz, R. C.(2013). Monitoring CO_2 Intrusion and Associated Geochemical Transformations in a Shallow Groundwater System Using Complex Electrical Methods. *Environmental Science & Technology*, *47*(1), 314–321. https://doi.org/10.1021/es301260e

De Silva, G. P., Ranjith, P. G., and Perera, M. S. (2015). Geochemical aspects of CO2 sequestration in deep saline aquifers: A review. *Fuel*, *155*, 128–143. https://doi.org/10.1016/j.fuel.2015.03.045

Druckenmiller, M. L., and Maroto-Valer, M. M. (2005). Carbon sequestration using brine of adjusted pH to form mineral carbonates. *Fuel Processing Technology*, *86*(14–15), 1599–1614

Gaasbeek, H., Goldberg, T., Koenen, M., Visser, W., Wildenborg, T., and Steeghs, P. (2014). Testing a simple and low-cost method for long-term (baseline) CO2 monitoring in the shallow subsurface. *Energy Procedia*, *63*, 3915–3922. https://doi.org/10.1016/j.egypro.2014.11.421

Hartai, E. (2012). Carbon dioxide storage in geological reservoirs. Institute of mineralogy and Geology.

Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., and Wilcox, J. (2019). An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations. *Frontiers in Climate*, *1*, 9. https://doi.org/10.3389/fclim.2019.00009

Kharaka, Y. K., Thordsen, J. J., Kakouros, E., Ambats, G., Herkelrath, W. N., Beers, S. R., Birkholzer, J. T., Apps, J. A., Spycher, N. F., Zheng, L., Trautz, R. C., Rauch, H. W., and Gullickson, K. S. (2010). Changes in the chemistry of shallow groundwater related to the 2008 injection of CO2 at the ZERT field site, Bozeman, Montana. *Environ Earth Sci*, 12.

Khudaida, K. J., and Das, D. B. (2014). A numerical study of capillary pressure–saturation relationship for supercritical carbon dioxide (CO2) injection in deep saline aquifer. *Chemical Engineering Research and Design*, *92*(12), 3017–3030. https://doi.org/10.1016/j.cherd.2014.04.020

Lee, J. H., Cho, J., and Lee, K. S. (2020). Effects of Aqueous Solubility and Geochemistry on CO_2 Injection for Shale Gas Reservoirs. *Scientific Reports*, *10*(1), 2071. https://doi.org/10.1038/s41598-020-59131-y

Liu, Q., and Maroto-Valer, M. M. (2011). Parameters affecting mineral trapping of CO_2 sequestration in brines: Parameters affecting mineral trapping of CO_2 sequestration in brines. *Greenhouse Gases: Science and Technology*, *1*(3), 211–222. https://doi.org/10.1002/ghg.29

Metz, B., Davidson, O., Coninck, H., Loos, M. and Meyer, L. (2005). IPCC special report on carbon dioxide capture and storage. Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III. (Vol. 1). Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III. Cambridge University Press

Pan, S. Y., Chen, Y. H., Fan, L. S., Kim, H., Gao, X., Ling, T. C., Chiang, P. C., Pei, S. L., and Gu, G. (2020). CO_2 mineralization and utilization by alkaline solid wastes for potential carbon reduction. *Nature Sustainability*, *3*(5), 399–405. https://doi.org/10. 1038/s41893-020-0486-9

Rabiu, K. O., Han, L., and Das, D.B (2017). CO2 Trapping in the Context of Geological Carbon Sequestration. In *Encyclopedia of Sustainable Technologies* (pp. 461–475). Elsevier. https://doi.org /10.1016/B978-0-12-409548-9.10124-1

Rabiu, K. O., Abidoye, L. K., and Das, D. B. (2020). Physico-chemical and dielectric parameters for the monitoring of carbon sequestration in basalt and silica media. *Environmental Technology & Innovation*,*20*, 101052. https://doi.org/10.1016/j. eti. 2020.101052

Rathnaweera, T. D., Ranjith, P. G., and Perera, M. S. A. (2016). Experimental investigation of geochemical and mineralogical effects of CO2 sequestration on flow characteristics of reservoir rock in deep saline aquifers. *Scientific Reports*, *6*(1), 19362. https://doi.org/10.1038/srep19362

Schmidt-Hattenberger, C., Bergmann, P., Bösing, D., Labitzke, T., Möller, M., Schröder, S., Wagner, F., and Schütt, H. (2013). Electrical Resistivity Tomography (ERT) for Monitoring of CO_2 Migration —From Tool Development to Reservoir Surveillance at the Ketzin Pilot Site. *Energy Procedia*, *37*, 4268 –4275. https://doi.org/10.1016/j.egypro.2013.06.329

Solomon, S. (2006). *Criteria for Intermediate Storage of Carbon Dioxide in Geological Formations*. The Bellona Foundation, https://network.bellona.

org/content/uploads/sites/3/Criteria_for_Intermediate_Storage_of_Carbon_Di oxide_in_Geological_Formations.pdf

Song, J., and Zhang, D. (2013). Comprehensive Review of Caprock-Sealing Mechanisms for Geologic Carbon Sequestration. *Environmental Science & Technology*, *47*(1), 9–22. https://doi.org/10.1021/es301610p

Song, Y., Sung, W., Jang, Y., and Jung, W. (2020). Application of an artificial neural network in predicting the effectiveness of trapping mechanisms on CO2 sequestration in saline aquifers. *International Journal of Greenhouse Gas Control*, *98*, 103042. https://doi.org/10.1016/j.ijggc.2020.103042

Voormeij, D. A. (2004). Geological, Ocean, and Mineral CO2 Sequestration Options: A Technical Review. *Geoscience Canada*, *31*(1), 12.

Wei, Y., Maroto-Valer, M., and Steven, M. D. (2011). Environmental consequences of potential leaks of CO_2 in soil. *Energy Procedia*, 4, 3224–3230. https://doi.org/10.1016/j.egypro.2011.02.239