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Editorial: CO_2 mineralization: A carbon storage technology for a sustainable future

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Editorial on the Research Topic
CO_2 mineralization: A carbon storage technology for a sustainable future

As atmospheric concentrations of carbon dioxide (CO_2) have continued to increase, a broad portfolio of carbon dioxide removal (CDR) options [aka, capture utilization and storage (CCUS) options and negative emission technologies (NETs)] have been proposed. CO_2 mineralization is a CDR process based on engineered weathering of rocks to fix CO_2 into stable carbonate minerals. It has the potential to mitigate CO_2 emissions into the atmosphere with permanent carbon sequestration at the scale of megatons per year. Recent works have focused on carrying it out underground (*in situ* CO_2 mineralization) and using it for direct air capture (DAC). Major challenges in the implementation of the process are the interaction of the carbonated fluid with the weathered rock and the selection of thermodynamic conditions that allows it to perform the operation at low temperatures and CO_2 pressure. To address these challenges, inorganic, organic, and even biological catalysts have been investigated and the coupling of CO_2 mineralization with valuable product synthesis such as bio-plastic and critical elements has also been explored. Despite almost three decades of research in CO_2 mineralization several questions on process kinetics, modeling, and optimization have not been answered, yet. But, at the same time, new avenues have opened for the application of the process, in particular, for solid and liquid waste treatment.

In this Research Topic, a combination of Original Research Articles is reported, spanning from different science and engineering disciplines, i.e., chemical and process engineering to geochemistry and mineralogy. The next paragraphs describe each of the published articles within the themes covered by the Research Topic.

The potential and the feasibility of measures to mitigate CO_2 emissions depend on specific conditions at the site of implementation such as the biophysical site characteristics and the availability of infrastructure and resources. The work by Borchers et al. analyzes the effect of these specific conditions on CDR. The authors selected 13 near-to-market CDR concepts, comprising direct air carbon capture (DACC), bioenergy with carbon capture and storage (BECC), and natural sink enhancement. The options with the highest CO_2 removal potentials are found to be: DACC farms, BECC with the combustion of biomass for the generation of heat and/or power (CHP), DACC combined with heating, ventilation, and air conditioning (HVAC), BECC with pyrolysis, BECC with biogas CHP, natural sink enhancement (NSE) due to enhanced rock weathering, NSE due to afforestation of cropland, NSE due to peatland rewetting, and NSE due to cover crops. The authors calculate that in 2050, the maximum CDR potential of the analyzed options will vary from 91 to 240 Mt CO_2/year, which counterbalances the amount of hard-to-abate emissions of 36–63 Mt CO_2. However, the successful implementation of the CDR concepts depends on the availability of carbon storage options, which are currently constrained by laws in Germany and therefore require new regulations and policy incentives.

The work by Dufourny et al. focuses on mineral carbonation of alkaline mine residues which is a CDR strategy that can be employed by the mining industry. The authors focus on the mineralogy and the reactivity of processed kimberlites and kimberlite ore rich in smectite mineral from Venetia (South Africa) and Gahcho Kué (Canada) diamond mines. They observe that smectites provide the fast reactivity of kimberlite to CO_2, opening the possibility of using other options than serpentine-, olivine-, hydrotalcite-and brucite-based tailings, such as those from smectite-rich sediment-hosted metal deposits and oil sands tailings. The article reports a comprehensive mineralogical characterization of the smectite-rich tailings. The smectite is $M^{m+}_{x/m}$ $Mg_3(Al_xSi_{4x})O_{10}(OH)_2{\cdot}nH_2O$ where $M^{m+}_{x/m}$ are hydrated interlayer cations such as Mg^{2+} and Ca^{2+} which react with CO_2 in the carbonation reaction. The smectite is Fe-, Ca-, Mg-, and Al-rich and contains some calcite ($CaCO_3$) at 2.0 to 10.3 wt.% in ore from Venetia and <2 wt.% in ore from Gahcho Kué. The presence of carbonates suggests the potential of carbonation for the mine tailing and the difference between the two deposits may indicate different carbonation strategies. On the basis of the results in this work and those in the literature, the authors propose a decision tree to select the most suitable carbonation process for a certain tailing extending the applicability of mine tailing carbonation beyond ultramafic mining residues.

Conventional materials for carbonation contain serpentine and olivine minerals. However, a major limitation in using such minerals is the formation of a surface passivation layer which inhibits the dissolution of the mineral and therefore the progress of the carbonation reaction. The article by Zeyen et al. proposes a technique to avoid the formation of the surface passivation layer on non-serpentinized magnesium silicates, which is based on attrition. The carbonation process is carried out inside a stirred bead mill where the continuous attrition between the residues and the bids helps remove the forming layer. Specifically, the authors investigate the carbonation of a mining waste, ferronickel slag, which is Mg- and Si-rich in the amorphous phase, and a crystalline ferrous forsterite (the Mg-end member of olivine). The article describes a very rigorous experimental protocol to perform the carbonation reactions in various combinations with mechanical activation. The authors conclude that concurrent attrition and carbonation (AC) is the best option, yielding more than 70% carbonation in 24 h. The residual product consists of micro-particles containing an unreacted core surrounded by an entanglement of nanometric grains of carbonates and amorphous silica, the result of the carbonation reaction, and an external shell of magnesium-depleted alumino-siliceous matrix result of the mechanical process. Future work by the authors will focus on the formulation of the reaction pathway.

Finally, the article by Abraham et al. presents a novel integration of two convectional processes for carbon emission mitigation, namely algae growth and CO_2 mineralization. The process has the aim to treat toxic wastewater while capturing CO_2 into bio-products. The authors test the effect of controlling pH by supplying bicarbonate anions to freshwater microalga *Scenedesmus obliquus* through the addition of solid carbonate minerals, specifically, a hydrated metastable form of Mg-carbonate named nesquehonite. The authors combine experimental activity with the development of a mathematical model coupled with geochemistry. The model describes the processes of algae growth and the carbonate dissolution within open-air reactors where the parameters were determined through the optimization of the online measurements. A variety of tests were run to provide experimental evidence of the positive effect of controlling the pH using carbonate minerals on the bio-products yield. Comparing the oil and fatty acid methyl esters (FAME) content of the conventional tests and those run with the carbonate addition, the authors conclude that the addition of carbonates helps a successful metabolic-based pH control of the system. This novel process integration extends the applicability of CO_2 mineralization beyond construction materials and toward a broad range of bio-products such as, for example, bio-fuels and bio-plastics.

With this Research Topic, we provide a sample of recent works on experiments, modeling, and optimization of CO_2 mineralization, as well as novel coupling options of CO_2 mineralization. The excellent contributions to this Research Topic are a demonstration of a highly active research community focused on CDR systems for a sustainable future.

Together they provide an overview of the state-of-the-art in the subject and the future need for research.

Author contributions

VP is the lead author of this manuscript. All authors have contributed to the writing of this editorial and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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