Review

Status of CO$_2$ mineralization and its utilization prospects

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Abstract

Action is currently being taken globally to mitigate global warming.The objective of reducing CO$_2$ emissions is not a burden for society but is a significant opportunity for evolution in various industries for the sustainable production of energy and the essential minerals, metals, and materials required for modern society. CO$_2$ mineralization is one of the most promising methods to effectively reduce CO$_2$ emissions via the formation of stable mineral carbonates. Accelerated mineral carbonation requires high capital costs for implementation. Accordingly, it has thus far not been economically feasible to carry out accelerated CO$_2$ mineralization alone. Accelerated CO$_2$ mineralization must be combined with other associated technologies to produce high-value products. The technical developments in enhanced metal recovery, nanomaterials, enhanced flotation, H$_2$ production and applications in the cement industry may be suitable options. The utilization and generation of valuable byproducts may determine the economic feasibility of CO$_2$ mineralization processes. The need for CO$_2$ reduction and utilization can contribute to driving the development of many innovative and sustainable technologies for the future benefit of society. The implementation of carbon taxation may also significantly motivate the development of these technologies and their potential application.

Keywords: CO$_2$ mineralization, mineral carbonation, enhanced metal recovery, global warming, passive carbonation, carbon capture utilization and storage

INTRODUCTION

With the approval of the Paris Agreement, more than 197 countries have agreed to reach carbon neutrality in order to achieve a temperature increase of less than 1.5 °C compared to the pre-industrial temperature level[1]. Actions to achieve this common goal include increasing carbon tax rates, decreasing the usage of fossil fuels in energy grids, encouraging the usage of renewable energies and the development of electric vehicles, and decreasing carbon emissions from industry. CO_2 mineralization[2-4], also known as mineral carbonation[5], is one of the most promising methods to effectively decrease CO_2 emissions. CO_2 mineralization transforms CO_2, as a greenhouse gas, into stable mineral carbonates, as shown in Eqs. (1) and (2), where "Me" represents a divalent metal, such as Mg^{2+}, Fe^{2+} or Ca^{2+}, and the corresponding $MeCO_3$ represents $MgCO_3$ (magnesite), $FeCO_3$ (siderite) or $CaCO_3$ (calcite), respectively. Suitable feed materials for CO_2 mineralization are abundant globally, including various divalent metal-containing silicate minerals, e.g., geological rocks of peridotites (ultramafic rocks containing < 45% SiO_2) and basalts (mafic rocks containing 45%-52% SiO_2), and oxide minerals, e.g., industrial waste of steel slags and fly ashes.

$$Me_2SiO_4 + CO_2 = 2MeCO_3 + SiO_2 \qquad (1)$$
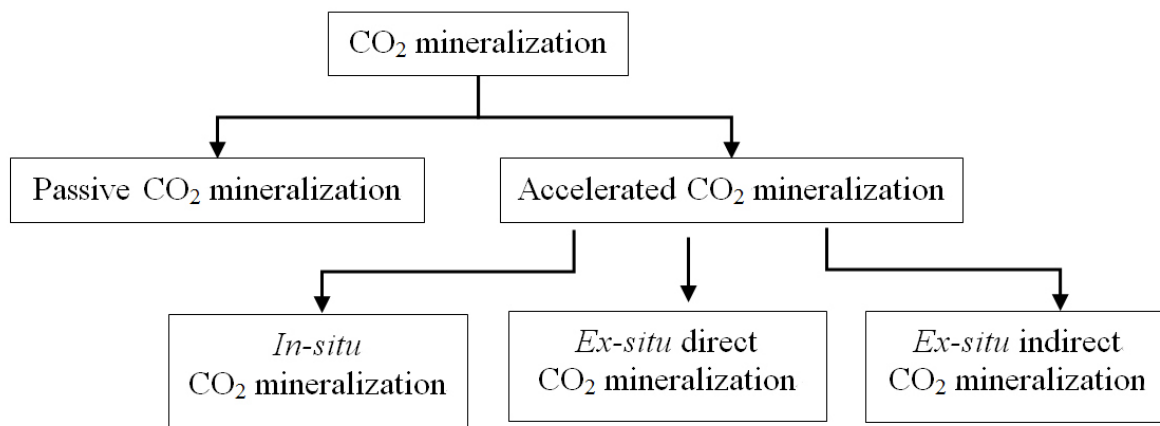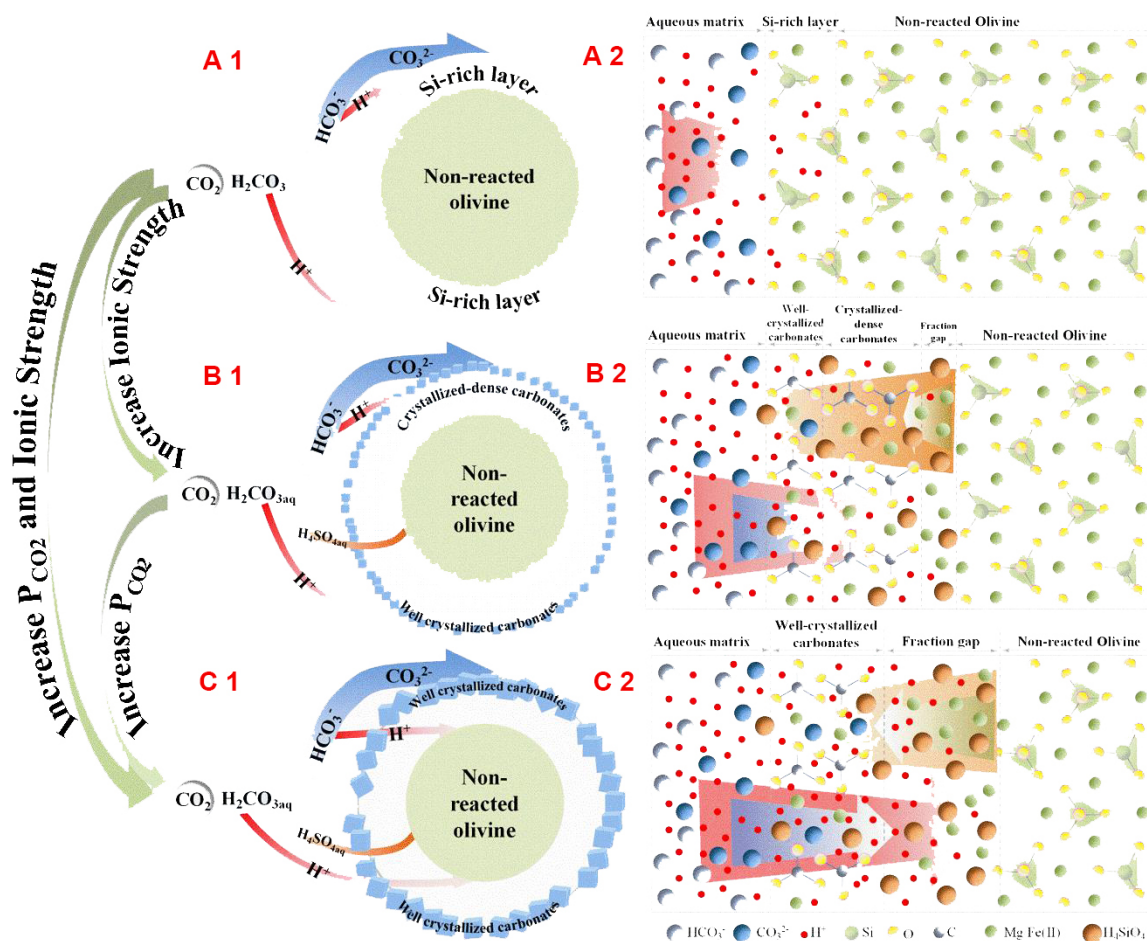
$$MeO + CO_2 = MeCO_3 \qquad (2)$$

CO_2 mineralization reactions can occur naturally but with very slow kinetics[6]. In order to have an impact on global warming mitigation, the current work focuses on how to accelerate natural CO_2 mineralization reactions[7]. Owing to the different methods and considerations, CO_2 mineralization can be subcategorized as passive[8-14], *in-situ*[15-25], *ex-situ* direct[2,3,5,26,27] or *ex-situ* indirect carbonation[6,28,29], as shown in Figure 1. Despite the different pathways to carbonation, the dissolution of silicates or oxides is generally the rate-limiting step for CO_2 mineralization[26,30-33]. Wang *et al.*[26] reported the variations of CO_2 mineralization of $(Mg,Fe)_2SiO_4$ (olivine) dependent on CO_2 pressure (PCO_2) and concentration of sodium salts, as shown in Figure 2. For a sodium salt concentration of < 0.32 mol/kg, the CO_2 mineralization is limited by diffusion through a silica-rich passivation layer. With a sodium salt concentration of > 0.32 mol/kg but a PCO_2 of > 21 bar, the rate-limiting step shifts to diffusion through a uniform carbonate passivation layer. With a sodium salt concentration of > 0.32 mol/kg and a PCO_2 of > 21 bar, the passivation layers disappear and the rate-limiting step becomes the dissolution of olivine. In fact, all the CO_2 mineralization pathways have enhanced the rate and extent of the dissolution of silicates and oxides.

Despite being a significant method of carbon capture, utilization and storage, CO_2 mineralization is dependent on the strict requirements of a high-pressure CO_2 supply, high temperature (> 150 °C), fine particle size (μm) and the usage of pressure autoclave reactors, and thus is still far from being cost-effective for commercial applications. It, therefore, may be necessary to combine it with other technologies to minimize capital costs. In this work, we review not only the status of the CO_2 mineralization but also the prospects for its future utilization for associated technologies.

PASSIVE CO$_2$ MINERALIZATION

For passive CO_2 mineralization, mineral carbonation occurs under atmospheric conditions without artificially using agitated reactors. The passive method utilizes the characteristics of natural weathering processes. Exposed rock is contacted with a CO_2-containing atmosphere, and slow carbonation occurs to remove CO_2 from the atmosphere. An example of passive mineral carbonation has been observed in Oman[34,35], as shown in Figure 3. Kelemen and Matter[34,35] estimated that the peridotite in the Sultanate of Oman alone may carbonate more than 1 billion tons of CO_2 per year. Owing to the minimum capital costs, passive CO_2 mineralization may be the optimal choice for mining industries with respect to waste

Figure 1. Schematic diagram of CO_2 mineralization methods.

Figure 2. Variations of CO_2 mineralization mechanism dependent on CO_2 pressure and concentration of sodium salts (reproduced from Wang *et al.*[26]).

utilization. Mining and metallurgical activities produce significant amounts of mine tailings with reduced particle size containing various silicate minerals, such as olivine, serpentine and pyroxene, which are
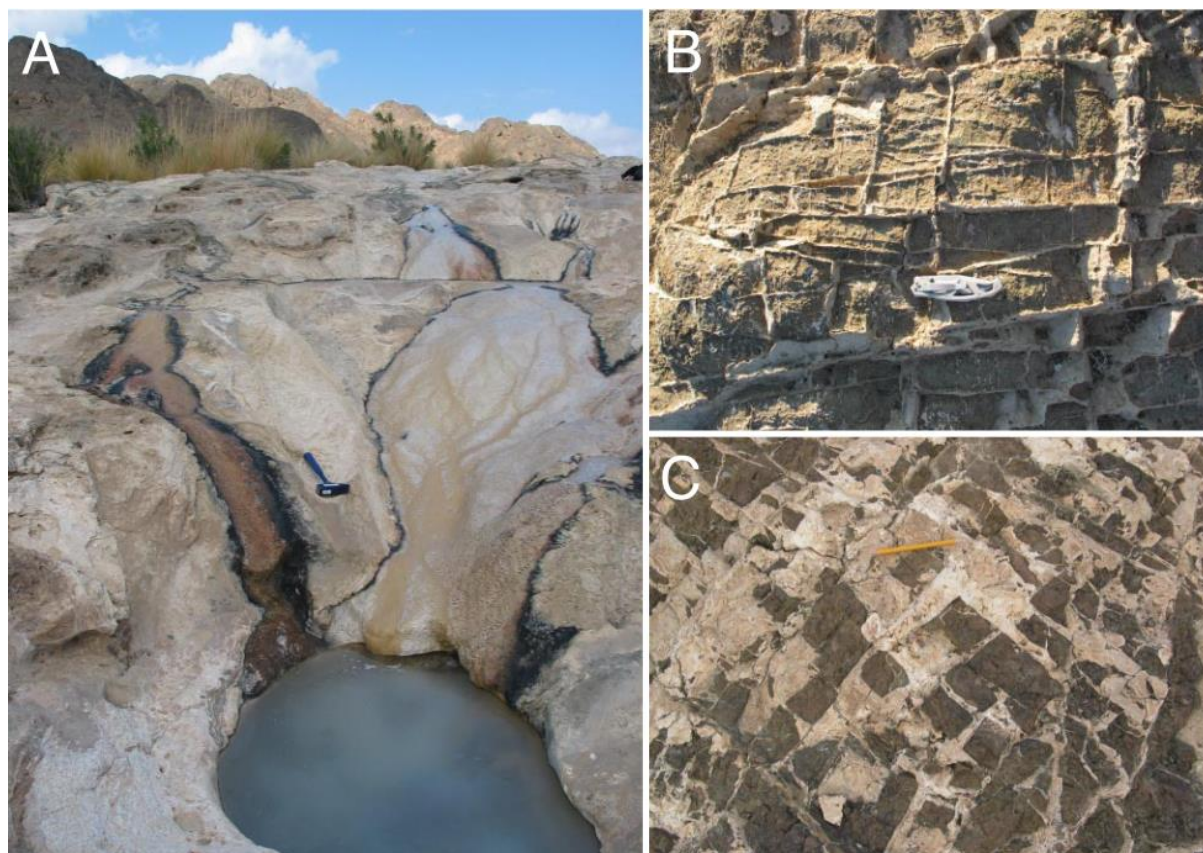
Figure 3. Natural CO_2 mineralization in Oman with white carbonate veins shown in (A), (B) and (C) (reproduced from Kelemen and Matter[34]).
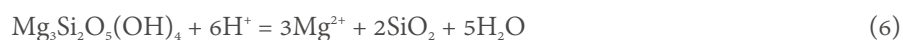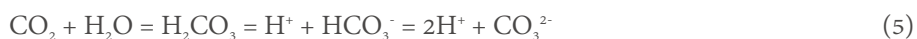
suitable for CO_2 mineralization. Therefore, mining and extraction companies are expected to utilize mine tailings to passively react with CO_2 from the atmosphere to form mineral carbonates for permanent storage.

Power *et al.*[8] found that the passive CO_2 mineralization rate is highly dependent on the brucite $[Mg(OH)_2]$ content in mine tailings[36]. The amount of brucite may account for 1 wt.%-15 wt.% of ultramafic mine tailings[8]. If all the brucite is reacted, as shown in Eq. (3), a substantial amount of emitted CO_2 can be removed from the atmosphere. In addition to the original brucite content, natural weathering of olivine to serpentine $[Mg_3Si_2O_5(OH)_4]$ can also generate brucite for CO_2 mineralization, as shown in Eq. (4).

$$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O \tag{3}$$

$$2Mg_2SiO_4 + 3H_2O = Mg(OH)_2 + Mg_3Si_2O_5(OH)_4 \tag{4}$$

Since the surface area of mine tailings in tailing ponds exposed to air is limited for the effective mineralization reaction, research has been focused on increasing the interactive area between mine tailings and CO_2. One of the corresponding solutions for passive CO_2 mineralization involves drilling boreholes in tailings and pumping air through the boreholes to enhance the weathering process[12,37,38]. An alternative solution is to utilize a CO_2-rich aqueous solution (carbonic acid) flowing through tailings to enhance the dissolution of divalent metals from silicate minerals, such as serpentine. With the consumption of protons from carbonic acid, the pH values gradually increase and the dissolved divalent metals finally precipitate as

mineral carbonates[11,39,40]. The corresponding chemical reactions [Eqs. (5)-(7)] occur in sequence. The dissolution of CO_2 from air to water provides protons to dissolve serpentine, and the produced mineral carbonate is usually hydrated since it is formed at atmospheric temperature.

$$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^- = 2H^+ + CO_3^{2-} \tag{5}$$

$$Mg_3Si_2O_5(OH)_4 + 6H^+ = 3Mg^{2+} + 2SiO_2 + 5H_2O \tag{6}$$

$$Mg^{2+} + CO_3^{2-} + xH_2O = MgCO_3 \cdot xH_2O \tag{7}$$

If considering CO_2 mineralization alone, the passive pathway may be the optimal option, owing to the low costs of carbon capture, pressurization, storage and transportation. Stakeholders in the mining industries, however, may attempt to enhance economic feasibility by utilizing the products of CO_2 mineralization. The future development of passive CO_2 mineralization may be combined with enhanced product utilization, in addition to enhancing the natural weathering process itself. The potential utilization may be enhanced metal recovery[11] and the formation of aggregates for the manufacturing of cement and construction materials[41,42].

IN-SITU CO_2 MINERALIZATION

Similar to the passive pathway, *in-situ* CO_2 mineralization injects CO_2-rich gas, a gas mixture or aqueous fluid underground to facilitate the carbonation reaction between CO_2 and underground mineralization without any mining activities. Thus far, the most successful example of this pathway is the CarbFix project in Iceland[15-23]. The CarbFix project dissolves pure CO_2 gas, or more recently, CO_2-H_2S gas mixtures, into down-flowing waters and pumps the aqueous fluid underground through a drilling well (2000 m deep), as shown in Figure 4. The target reactive rocks are basalts, which are some of the most common types of rocks on Earth[23]. In order to monitor the reaction status underground, several monitoring wells have also been drilled. It is found that ~95% of the injected CO_2 was successfully mineralized to stable mineral carbonates in less than two years[23]. The corresponding fundamentals are similar to passive carbonation, i.e., the basalt rocks dissolved to release divalent metal ions, mainly Ca^{2+}, with the attack of CO_2-dissolved water fluid. With the consumption of protons by basalts, the pH increased and the released divalent metal ions precipitated as mineral carbonates.

Motivated by the success of the CarbFix project, *in-situ* mineralization is also being applied across the USA through the Big Sky Carbon Sequestration Partnership[43]. Peridotites, another very common type of rock on Earth[25,44], have also been tested for *in-situ* mineralization. Different from basalts, peridotites usually have low permeability and porosity[25]. As a result, *in-situ* CO_2 mineralization with peridotites has not achieved obvious progress yet[45]. In the future, the *in-situ* pathway may continue to play an important role in CO_2 mineralization in geological fields. The potential application may depend on the suitability of silicate resources, seismic activities, permeability and porosity in geology and mineralogy. In addition, *in-situ* CO_2 mineralization may also be utilized for enhanced oil recovery to increase credits[46-49].

EX-SITU DIRECT CO_2 MINERALIZATION

Since both passive and *in-situ* CO_2 mineralization still require the carbonation reaction, which takes several years to complete, many researchers are trying to accelerate the process for completion in hours for achieving effective global warming mitigation. Nowadays, *ex-situ* direct CO_2 mineralization is the most popular research work at the laboratory scale. Since the chemical reaction in an aqueous matrix or at least with water vapor is much faster than the direct gas-solid reaction[50-52], *ex-situ* direct CO_2 mineralization generally occurs within an aqueous solution. To maximize the kinetics, the *ex-situ* direct aqueous CO_2
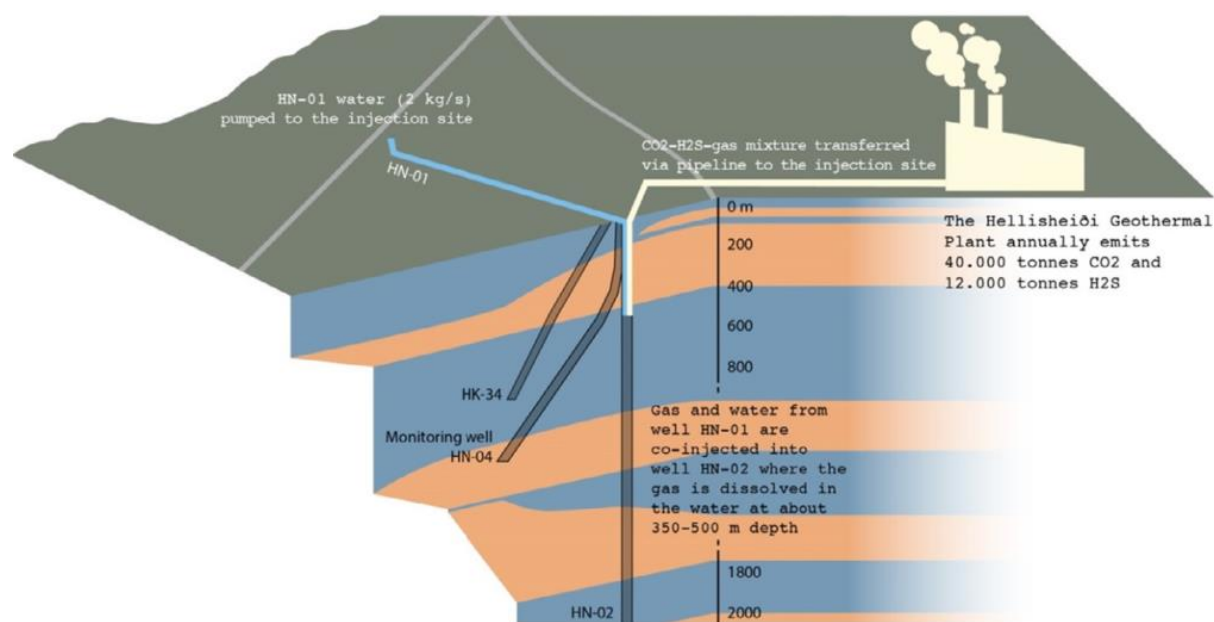
Figure 4. Schematic diagram of *in-situ* CO_2 mineralization of CarbFix project in Iceland (reproduced from Snæbjörnsdóttir *et al.*[15]).

mineralization usually needs strict reaction requirements, including high temperature and CO_2 pressure, fine particle size and the usage of pressure reactors (autoclaves). Sodium salts, for example, sodium bicarbonate and sodium chloride, may also be added to the solution for carbonation to significantly accelerate the mineral carbonation process[26,27,53-57].

Wang *et al.*[5,26,27] used pure olivine for CO_2 mineralization and achieved a 78% carbonation efficiency (based on the reacted olivine fraction) in 5 h under the conditions of PCO_2 = 34.5 atm, 175 °C, particle sizes of < 25 μm, sodium bicarbonate and sodium chloride at one molality and a 10% pulp density (% solid fraction in the slurry mixture). Around 84 kg CO_2 per ton of olivine per hour were stabilized as mineral carbonates. A high PCO_2 and concentration of sodium salts were important for addressing the difficulty of diffusion through passivation layers. As shown in Figure 2, Wang *et al.*[26] further explained that the addition of sodium salts can accelerate the carbonation reaction via the dissolution of aqueous silica (H_4SiO_4) from olivine to the bulk solution, which subsequently decomposed into solid amorphous silica and quartz. High PCO_2 can enhance the supply of protons for the enhanced dissolution of olivine and the supply of (bi-)carbonate ions for crystalline mineral carbonate precipitates. The conditions of high PCO_2 and elevated temperature resulted in the usage of a pressure autoclave vessel, which markedly increased the capital costs for CO_2 mineralization[58]. An energy reactor[59-62] was designed to meet the requirements of high pressure and temperature by utilizing gravity and exothermic reactions of CO_2 mineralization and to replace the autoclave usage. The application of the energy reactor utilizes differences in altitude in the terrain of sites. Similarly, a concurrent grinding method was designed to remove surface passivation layers under ambient pressure to avoid using an autoclave vessel[31,63-67].

Wang *et al.*[5] also investigated the direct aqueous CO_2 mineralization of natural silicate samples and discovered that olivine was the dominant reactive mineral, while the other silicate minerals, including serpentine and pyroxene, were not involved in the CO_2 mineralization reaction. Therefore, the current direct carbonation work in slurry systems focuses on using olivine to represent reactive silicates. Correspondingly, serpentine minerals required heat pre-treatment to convert to olivine for effective

carbonation[55,58]. The capital cost, therefore, may further increase[68,69]. After heat treatment at ~650 °C, serpentine became reactive for carbonation and exhibited faster kinetics, even when compared to olivine. The specific surface area was increased owing to the fractures of particles during heat treatment. Wood *et al.*[70] further discovered the effects of Fe(II) content in olivine on CO_2 mineralization. Fe(II) in olivine may convert to hematite (Fe_2O_3) during carbonation and thus show a competitive reaction to prevent the CO_2 mineralization process. As a result, the higher the Fe(II) content in olivine, the more difficult the CO_2 mineralization. A reductive gas, 1% H_2, has been recommended as a supply for the mineralization system to inhibit the oxidation of Fe(II) and accelerate the CO_2 mineralization process. This finding was verified by the work of Wang *et al.*[71], where a gas mixture of 5% H_2S and 95% CO_2 can increase the carbonation efficiency of olivine by up to 26% compared with a pure CO_2 gas supply. This may also be the reason why the CarbFix project uses a CO_2-H_2S gas mixture sequestered over 95% CO_2 in a shorter period than expected.

In addition to natural silicate minerals, industrial waste can also be utilized for direct aqueous CO_2 mineralization, such as steel-making slags[72-75] and blast furnace slags[76], coal fly and bottom ashes[77,78] and smelter waste (lead and copper slags)[79]. The mineral carbonation of industrial waste may be more interesting for both CO_2 emission reduction and waste hazard management because the waste usually shows higher chemical reactivity than natural silicates and fine particles.

However, there has still been no significant decrease in capital costs due to the characteristics of the strict requirements thus far. Therefore, it is not suitable to carry out *ex-situ* direct aqueous CO_2 mineralization alone[3]. The product value may be the main driver for mineral carbonation[60]. In the future, research into direct aqueous CO_2 mineralization may be concentrated on the utilization of products or its combination with other associated technology.

EX-SITU INDIRECT CO_2 MINERALIZATION

Since the dissolution of divalent metal-containing silicates and oxides is usually the rate-limiting step, *ex-situ* indirect CO_2 mineralization has also been developed. The silicates or oxides are first dissolved to release divalent metals, followed by precipitation as mineral carbonates under varied conditions. The typical routes for the *ex-situ* indirect pathway are the temperature swing process[29,80] and the pH swing process[81].

Zevenhoven *et al.*[80,82,83] developed the Åbo Akademi (ÅA) route on the temperature-swing process. As shown in Figure 5, the silicate mineral is first dissolved as magnesium sulphate at ~400 °C by ammonium sulphate, followed by magnesium extraction as magnesium hydroxide at < 100 °C and CO_2 mineralization at ~450 °C. The advantages of the ÅA route are the utilization of the released heat of the CO_2 mineralization reaction and the recycling reagent of ammonium sulphate.

The other typical process is based on the pH-swing route[28,84-86]. The silicate or oxide minerals are firstly dissolved by an acid at a low pH value to release divalent metal ions in the aqueous solution, followed by adding an alkali to increase the pH and precipitating as mineral carbonates. During the pH-swing process, the acid and alkali reagents are difficult to recycle. Thus, the overall costs may still be a concern during the process because they simply shift from equipment and operation to the consumption of reagents. Therefore, the application of pH-swing CO_2 mineralization is highly dependent on the recyclability of the reagents. Ammonium chloride might be a good choice for recycling, as stated by Hosseini *et al.*[87]. In addition to natural silicates and oxides, indirect CO_2 mineralization can be tested on various slags and waste[51,88,89].
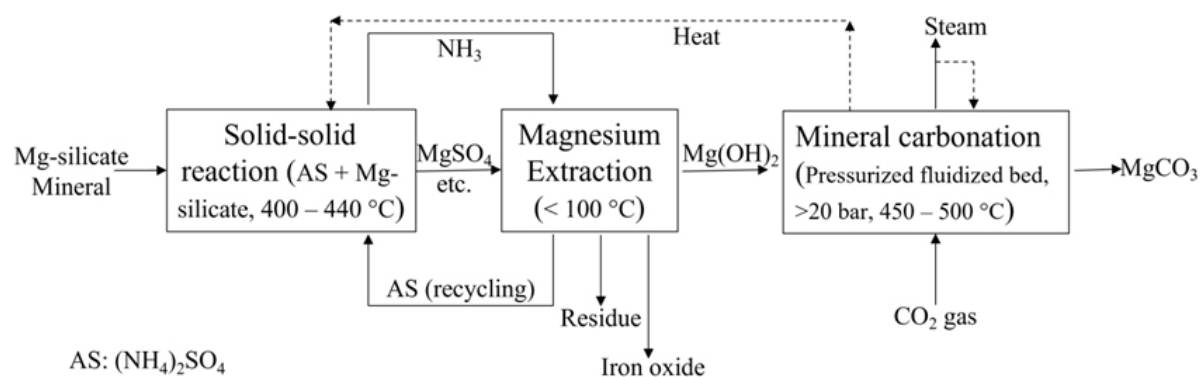
Figure 5. Schematic diagram of typical ÅA route (reproduced from Fagerlund *et al*.[82]). ÅA: Åbo Akademi.

In the future, *ex-situ* indirect CO_2 mineralization may continue to play an important role, owing to meeting the general sequence of CO_2 mineralization and high carbonation efficiency. Nevertheless, challenges remain in reducing the capital costs of reagent consumption to make the whole CO_2 mineralization process economical. Similar to direct CO_2 mineralization, the utilization of byproducts or its combination with other technologies represent promising routes for development.

CO_2 MINERALIZATION IN CEMENT INDUSTRY

Although there is no difference in the CO_2 mineralization method used in the cement industry, CO_2 emissions in cement and concrete represented ~27% of global industrial CO_2 emissions[90] at 1.45 ± 0.20 Gt CO_2/year in 2016[91]. Based on the current cement consumption level, global cement production may further grow by 12%-23% by 2050 to meet the needs of the rising global population, urbanization and infrastructure developments[90]. Therefore, it is necessary to consider CO_2 emission reduction in the cement industry[92] for the common carbon neutral goal by 2050. The main reactive material of cement is calcium silicate hydrate (C-S-H), which is also suitable for CO_2 mineralization[90,93,94]. Liu *et al*.[94] investigated the carbonation behavior of C-S-H in cement and confirmed that it has promising potential for CO_2 mineralization. Wang *et al*.[93] reviewed the carbonation work of cement-based materials and found that CO_2 mineralization could improve the mechanical performance of recycled aggregates and concretes. Thonemann *et al*.[95] also reported that direct aqueous CO_2 mineralization, carbonation mixing and curing in the cement industry are significant for CO_2 emission reduction. The products of direct aqueous CO_2 mineralization can be utilized as supplementary cementitious materials or as aggregates in concretes. The carbonation curing of cement-based products in a pressurized CO_2 atmosphere can form a hybrid binder structure of C-S-H and calcite. Carbonation mixing, i.e., purging CO_2 gas into the mixture of cement, aggregates, water and admixtures, can form $CaCO_3$ nanoparticles and can thus increase the compressive strength of the concrete or reduce the usage of the binder in turn.
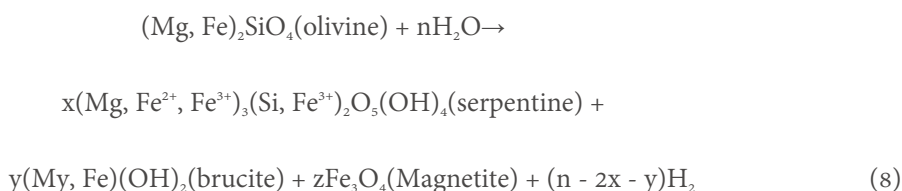
CO_2 MINERALIZATION AND UTILIZATION

Thus far, almost all CO_2 mineralization work has proved not to be economically profitable. It is therefore not sustainable for stakeholders to carry out CO_2 mineralization without the motivation of profits. There has been a consensus that accelerated CO_2 mineralization should be utilized with other technologies to minimize costs[3,5,48,60]. The other technologies include, but are not limited to, enhanced metal recovery[5,48,71,96,97], nanomaterials[98,99], enhanced flotation[100] and H_2 production[101-104].

Wang *et al.*[71] tried to utilize the *ex-situ* direct aqueous CO_2 mineralization of pure olivine for concurrent enhanced nickel recovery, as shown in Figure 6. With the supply of a gas mixture containing 95% CO_2 and 5% H_2S, the released nickel (and cobalt) ions from olivine, owing to the CO_2 mineralization reaction, which were previously considered as non-recoverable, were converted to nickel sulfide together with limited ferrous sulfide precipitates, whereas the magnesium and ferrous ions of olivine precipitated as stable mineral carbonates. The gas mixture supply of CO_2 containing 5% H_2S can make the sulfidization of nickel (cobalt) selective over iron and magnesium. Wang *et al.*[97] further tested the CO_2 mineralization and concurrently enhanced metal recovery on the real tailings of a copper-nickel-sulfide mine under development in Minnesota. The test results also proved that the utilization of CO_2 mineralization with concurrently enhanced metal recovery is suitable for ultramafic mine tailings. We are currently working on CO_2 mineralization and the concurrent metal extraction from laterites.

Zappala *et al.*[105] also utilized *ex-situ* indirect aqueous CO_2 mineralization for nickel leaching from a saprolite laterite, as shown in Figure 7. A triethylamine reagent was used for recyclability by varying the temperature. The laterite was first leached by dilute sulfuric acid to leach out the metals, followed by the gradual addition of triethylamine to raise the pH values and thus precipitate impurities, including iron and aluminum. Nickel can be precipitated by varying the pH, owing to the gradual addition of triethylamine, while magnesium remained in the aqueous solution. The magnesium ions from the aqueous solution can precipitate as magnesite with the further addition of triethylamine and a supply of CO_2-containing flue gas. The added triethylamine can be recovered as gas by increasing the temperature to 100 °C and correspondingly a dilute sulfuric acid solution was regenerated. Olivine was the dominant reactive mineral during the process. In this case, the consumption of acid and reagent can be reduced. The flow sheet in Figure 7 was further optimized more recently by emerging the regeneration step into the leaching step[105]. Hamilton *et al.*[11] also suggested the use of passive CO_2 mineralization of ultramafic mine tailings through heap leaching for potential metal recovery.

Stopic *et al.*[98] synthesized nanosilica through the *ex-situ* direct aqueous CO_2 mineralization of olivine at 175 °C and > 100 bar PCO_2. Yin *et al.*[99] utilized the direct aqueous CO_2 mineralization of fly and waste ashes to synthesize nanoscale calcium carbonate in a matrix of sodium glycinate or monoethanolamine solutions with a surfactant (cetyl trimethyl ammonium bromide). Bashir Wani *et al.*[100] used CO_2 as a conditioning agent for the froth flotation of nickel sulfide from an ultramafic nickel ore. With the inclusion of CO_2 prior to flotation, some monohydroxide complexes ($CaOH^+$ and $MgOH^+$) reacted with CO_2 to form mineral carbonates and increase the electrostatic repulsion between the nickel-containing mineral pentlandite and gangue minerals. As a result, the nickel pentlandite recovery and grade can also increase by 10% and 4%, respectively. Wang *et al.*[101-104] even utilized the hydrothermal reaction of olivine at 300 °C within a sodium bicarbonate aqueous solution to simultaneously achieve CO_2 mineralization and H_2 production. The overall reaction is shown in Eq. (8). At 300 °C, olivine transformed into serpentine, brucite and magnetite, and H_2 gas was released through an enhanced serpentinization process. The formed brucite can easily sequester CO_2 to produce magnesite as a stable carbonate. Wang *et al.*[101] further showed that pyroxene can accelerate this hydrothermal reaction for H_2 production, as shown in Figure 8.
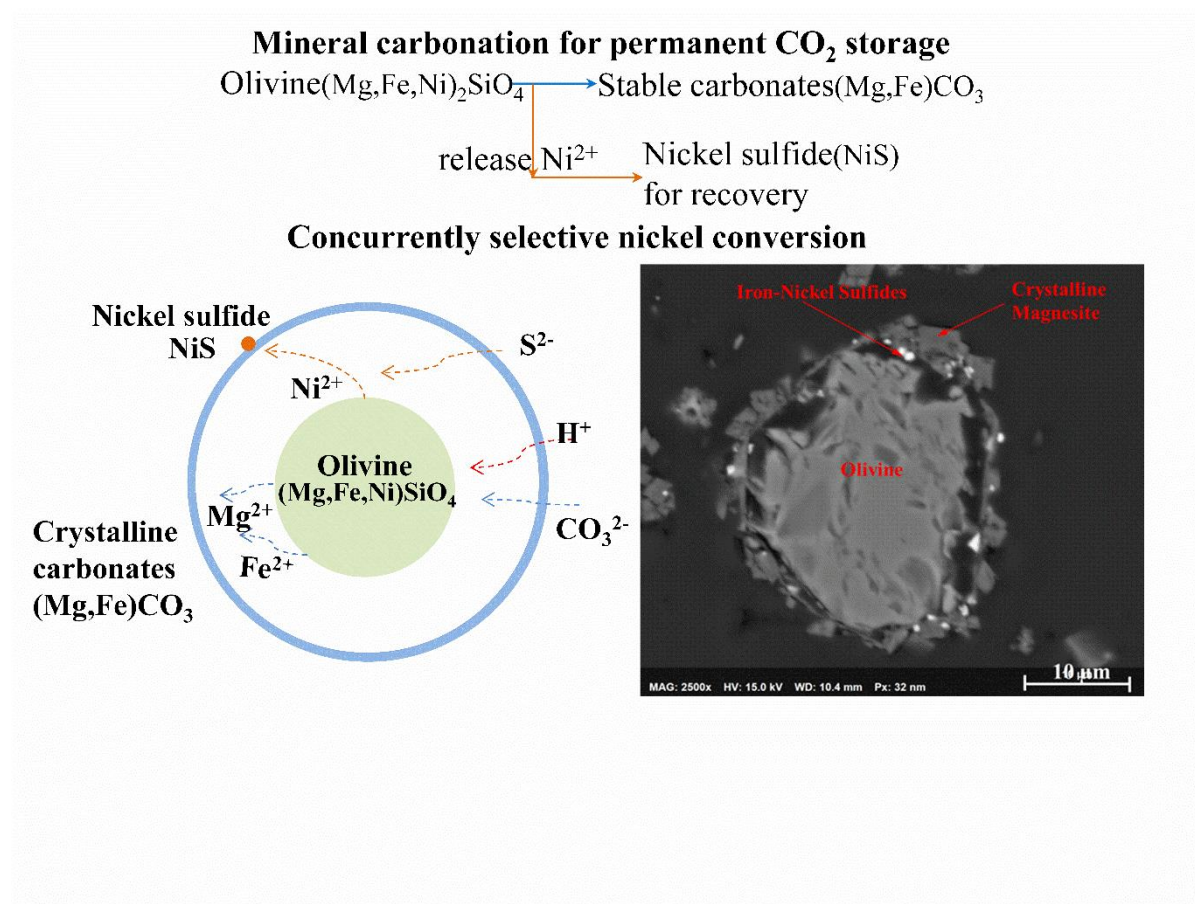
$$(Mg, Fe)_2SiO_4(olivine) + nH_2O \rightarrow$$

$$x(Mg, Fe^{2+}, Fe^{3+})_3(Si, Fe^{3+})_2O_5(OH)_4(serpentine) +$$

$$y(My, Fe)(OH)_2(brucite) + zFe_3O_4(Magnetite) + (n - 2x - y)H_2 \quad (8)$$

Figure 6. Schematic diagram of CO_2 mineralization and concurrent nickel sulfidization (reproduced from Wang *et al.*[71]).
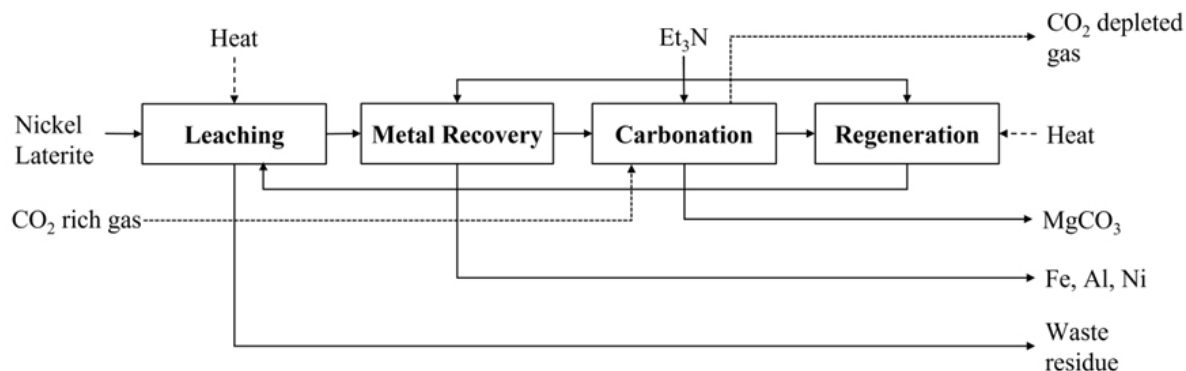

Figure 7. Process flow diagram of *ex-situ* indirect aqueous CO_2 mineralization for nickel leaching from a saprolite laterite (reproduced from Zappala *et al.*[105]). Et_3N represents triethylamine.

There are numerous possibilities for simultaneously achieving CO_2 mineralization and the corresponding utilization. The utilization may determine whether the CO_2 mineralization process is economically favorable. There is also no doubt that further process developments are needed for future scalability[106]. CO_2 emission reduction should be considered as an opportunity for evolution in various industrial productions. The need for CO_2 reduction and utilization can contribute to considerable developments in many
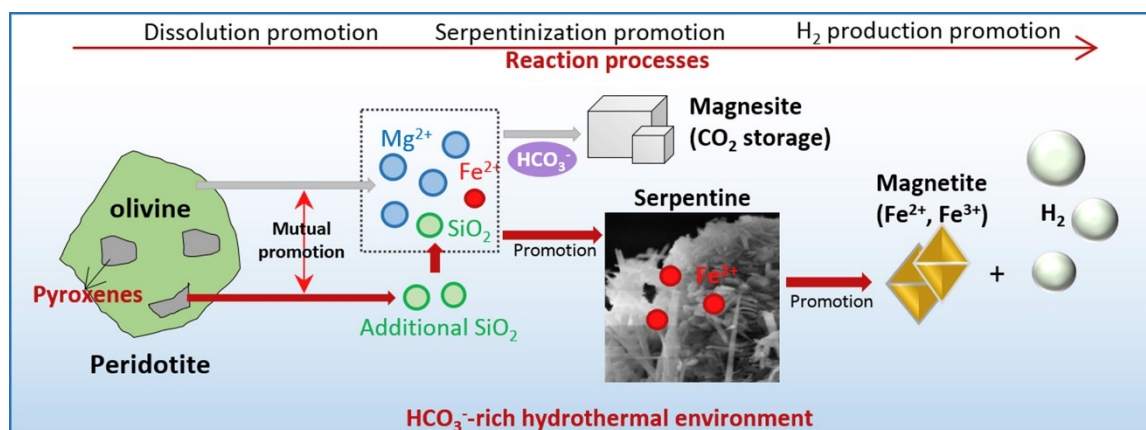
Figure 8. Schematic diagram of *ex-situ* direct aqueous CO_2 mineralization and utilization for H_2 production (reproduced from Wang *et al.*[101]).

innovative and sustainable technologies.

CARBON TAXATION

The development of CO_2 mineralization and the evolution of various industrial productions are closely related to governmental policies. *Ex-situ* direct aqueous CO_2 mineralization has so far not been economically feasible. The corresponding capital cost for using olivine and serpentine considering a 3%-5% inflation rate is $68-$112 and $150-$300 per ton of sequestered CO_2, respectively[58,107]. Carbon taxation is one of the most important and direct policies to affect the developments in carbon mineralization. At present, many countries have implemented carbon tax to encourage efforts on CO_2 emission reduction. The federal government of Canada has passed the *Reference re Greenhouse Gas Pollution Pricing Act* and set the carbon tax at Canadian Dollar (CAD) $50/ton CO_2 in 2022 but will reach CAD $95 by 2025 and CAD $170 by 2030 with an increasing rate of CAD $15 each year, as shown in Figure 9. Although no carbon taxation has formally been approved in the USA, there have been numerous proposals, including the *Climate Action Rebate Act* (Coons-Feinstein), the *America Wins Act* (Larson), and so on[108]. For example, based on the *Climate Action Rebate Act*, a carbon tax in the USA would be USD $45 in 2022 and reach USD $165 by 2022 and USD $240 by 2035 with an increasing rate of USD $15 each year, as shown in Figure 9. Similar to the carbon tax, China implemented a national carbon trading scheme at ~25 yuan/ton in 2021, which will likely increase to 35.5 and 46.5 yuan/ton by 2025 and 2030, respectively[109]. In Europe, the European Union Emissions Trading System allows the trade of greenhouse gas emissions on the market[110,111]. In 2022, the carbon permits trading in the EU market is expected to reach €69-€98/ton CO_2[111]. With the motivation of carbon credits, the CO_2 mineralization process may become economically feasible after 2026 based on carbon taxation in the USA.

The utilization of the CO_2 mineralization process may considerably accelerate the feasibility of its economics. For example, the carbonation of olivine containing 0.27% nickel may be utilized for nickel recovery[71,97]. If each ton of CO_2 sequestered through carbon mineralization of olivine can achieve 5 kg of nickel recovery, then the nickel credits can reach $112/ton of CO_2 based on the current nickel price on the market of $11/lb. As a result, the total benefits owing to CO_2 mineralization can outweigh the corresponding capital cost of the carbonation process, as shown in Figure 9. If the direct utilization of CO_2 mineralization can be applied to laterites, which contain > 1% nickel, the total benefits may far outweigh the capital cost and thus may be applicable. Therefore, both the carbon taxation and utilization of carbon mineralization are significant for its potential application. In contrast, it is a sign for industrial production to evolve and meet
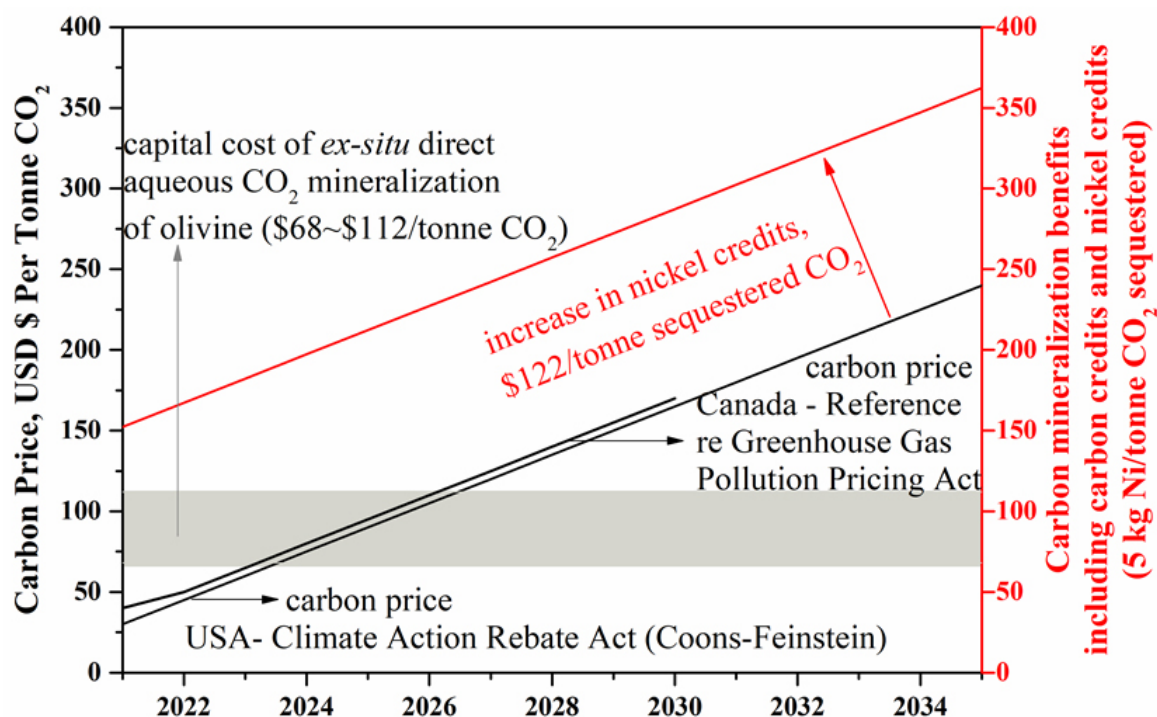
Figure 9. Carbon price in Canada and USA and potential CO_2 mineralization benefits including carbon credits and nickel credits. The capital cost of *ex-situ* direct aqueous CO_2 mineralization is based on Huijgen *et al.*[107] and O'Connor *et al.*[58] and recalculated with a 3%-5% inflation rate. The potential nickel credit is based on a nickel content of 0.27% in olivine, nickel recovery by utilizing mineral carbonation and the current nickel price on the market of $11/lb.

carbon emission reductions at least by 2030, otherwise they may need to address the increasing pressure from carbon taxation.

CONCLUSION

This review has considered various CO_2 mineralization technologies and their prospects for potential developments in their utilization and in the cement industry. The utilization may determine whether the CO_2 mineralization process is economically favorable. Thus far, passive CO_2 mineralization may be the dominant method before the other methods are applied into commercialization, because of its low capital cost for carbon capture, pressurization, storage and transportation. *In-situ* CO_2 mineralization is important and depends on the suitability of silicate resources, seismic activities, permeability and porosity in mineralogy and geology. *Ex-situ* CO_2 mineralization, especially the direct approach, and the corresponding utilization are under rapid development and may play a dominant role in CO_2 emission reduction in the forthcoming decades. Suitable utilization may include enhanced metal recovery, hydrogen production and nanomaterials production. The application of CO_2 mineralization in the cement industry is also important to effectively reduce CO_2 emissions. Carbon taxation can accelerate the economic feasibility of applying for CO_2 mineralization. Overall, CO_2 emission reduction should be considered as an opportunity for evolution in various industrial productions. The need for CO_2 reduction and utilization can contribute to the considerable development of many innovative and sustainable technologies for a better world in the future.

DECLARATIONS
Authors' contributions
Conceptualized, designed, and wrote the paper: Wang F

Supervised and edited the paper: Dreisinger D

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